The Causes and Consequences of Divergence between the Air Traffic Controller State Awareness and Actual System State

by

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Abstract

Divergence is an inconsistency between the human's system state awareness and the actual system state. This research investigated divergence potential in air traffic controllers and identified controller divergence causes and consequences. Based on this investigation, approaches to minimize controller divergence and its consequences were identified for current air traffic control systems and future systems where unmanned aircraft will be integrated.

Prior studies identified pilot divergence as a factor in several recent aircraft accidents and could be a factor for controllers. The future addition of unmanned aircraft in national airspace is a significant change which will affect the pilot and controller relationship and presents an opportunity to consider divergence before procedures are developed.

To understand how to minimize divergence and its consequences, this research developed a divergence cause and consequence framework and a cognitive process framework. The cause and consequence framework was developed using established risk analysis methods. The cognitive process framework was developed using established cognitive process and human error approaches. This research refined these frameworks and demonstrated their utility in an investigation of historical air traffic control accidents. They were then used to identify divergence vulnerabilities in a future unmanned aircraft-integrated national airspace.

Air traffic control cases were analyzed between 2011 and 2015 using the framework to understand causes and consequences of controller divergence. Twenty-seven (sixty-four percent) of these cases contained controller divergence contributing to the hazardous consequence. Although divergence causes and states varied, the most common event sequence included a diverged controller inducing an aircraft-to-aircraft conflict. These cases provided insight for system mitigations to reduce divergence causes and the consequentiality should it occur.

The potential emergence of controller divergence with the integration of unmanned aircraft in national airspace was then investigated. Field studies of controllers experienced managing unmanned aircraft identified important differences between manned and unmanned aircraft. The framework was then used to analyze these potential divergence vulnerabilities. Observables, specifically intent, appear more challenging to perceive yet crucial for controller projection of unmanned aircraft position due to their lack of onboard human perception, lost link, and automated operations. Hazardous consequences may be more likely due to the inability for unmanned aircraft to provide mitigations.

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AAL	American Airlines
AAR	Aviation Accident Report
ACAS	Airborne Collision Avoidance System
ADD	Aircraft-Derived Data
ADS-B	Automatic Dependent Surveillance-Broadcast
AFB	Air Force Base
AFI	Air Force Instruction
AGL	Above Ground Level
AMASS	Airport Movement Area Safety System
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ASDE-X	Airport Surface Detection Equipment model X
ASR	Airport Surveillance Radar
ASRS	Air Route Surveillance Radar
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATCT	Air Traffic Control Tower
ATM	Air Traffic Management
ATOP	Advanced Technologies and Oceanic Procedures
BAFBI	Beale Air Force Base Instruction
BLOS	Beyond Line Of Sight
CA	Conflict Alert
CAFBI	Creech Air Force Base Instruction
CAL	China Airlines
CAST	Commercial Aviation Safety Team
CFIT	Controlled Flight Into Terrain
CFR	Code of Federal Regulations
COA	Certificates of Authorization
CONOPS	Concept of Operations
CONUS	Continental United States
CPDLC	Controller-Pilot Data Link Communications
CS	Control Station
CTAF	Common Traffic Advisory Frequency
CTAS	Center-TRACON Automation System
CVR	Cockpit Voice Recorder
DoD	Department of Defense
DoT	Department of Transportation
DVE	Degraded Visual Environment
EAFBI	Edwards Air Force Base Instruction
EGPWS	Enhanced Ground Proximity Warning System
ERAM	En Route Automation Modernization
ETA	Event Tree Analysis
EVO	Equivalent Visual Operations
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FDR	Flight Data Recorder
FL	Flight Level
FLM	Front Line Manager

FPS	Flight Progress Strips
FTA	Fault Tree Analysis
GAO	Government Accounting Office
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HAFBI	Holloman Air Force Base Instruction
HATR	Hazardous Air Traffic Report
HFACS	Human Factors Analysis and Classification System
HIP	Human Information Processing
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IPO	Input-Process-Output
KAL	Korean Airlines
LL	Lost Link
LOS	Line Of Sight
LoSS	Loss of Standard Separation
MAC	Mid-Air Collision
MOA	Military Operations Area
MRU	Military Radar Unit
MSAW	Minimum Safe Altitude Warning
MSL	Mean Sea Level
MVA	Minimum Vectoring Altitude
NAFBI	Nellis Air Force Base Instruction
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NextGen	Next Generation Air Transportation System
NMAC	Near Mid-Air Collision
NORDO	No Radio
NOTAM	Notices To Airmen
NTSB	National Transportation Safety Board
PARC	Performance-based operations Aviation Rulemaking Committee
PIREP	Pilot Report
RA	Resolution Advisory
RAPCON	Radar Approach Control
RF	Radio Frequency
RPA	Remotely Piloted Aircraft
RVSM	Reduced Vertical Separation Minima
SA	Situation Awareness
SAA	Sense-And-Avoid
SCAT	Systematic Cause Analysis Technique
SOP	Standard Operating Procedures
SSR	Secondary Surveillance Radar
STAMP	Systems-Theoretic Accident Model and Processes
STANAG	Standardization Agreement
STCA	Short Term Conflict Alert
SUA	Special Use Airspace
TA	Traffic Advisory
TAS	Traffic Advisory System
TCAS	Traffic Collision and Avoidance System

TRACON	Terminal Radar Approach Control
TSD	Traffic Situation Display
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UASO	Unmanned Aircraft System Operator
US	United States
USAF	United States Air Force
UTM	UAS Traffic Management
VFR	Visual Flight Rules
VLO	Visual Look Out
VLOS	Visual Line Of Sight
VMC	Visual Meteorological Conditions
WAIT	Work Accidents Investigation Technique
WG	Working Group
WSMR	White Sands Missile Range

1 Introduction

Divergence is an inconsistency between the human's system state awareness and the actual system state (Silva, 2016). Inconsistencies between air traffic controllers and the system they control was highlighted as a vulnerability to safety risk within the Air Traffic Control (ATC) community (Performance-based operations Aviation Rulemaking Committee/Commercail Aviation Safety Team Flight Deck Automation Working Group, 2013), and has been shown to be a contributing factor in many recent aircraft accidents (Silva, 2016). This thesis hypothesizes controller divergence is a major risk area in the National Airspace System (NAS). At the same time, integrating Unmanned Aircraft Systems (UAS) in the NAS is a significant change which will affect the relationship between pilots and controllers and may also create opportunities for divergence. This research attempts to understand how to minimize controller divergence while they manage a human-integrated system by examining divergence causes and consequences in the ATC domain. To accomplish this objective, a framework of the causes and consequences of air traffic controller divergence was developed along with a framework of air traffic controller cognitive processes. The utility of these frameworks was demonstrated with an historical case study investigation. The frameworks were then used to identify opportunities and divergence vulnerabilities in a future system, an UAS-integrated NAS.

1.1 Divergence

Divergence is formally defined as an inconsistency between the human's system state awareness and the actual system state (Silva, 2016). Human understanding while operating a complex system, from driving a car to flying an airplane or managing a factory is seldom perfect. Luckily, perfection is seldom required. First of all, some system states do not need to be understood. For example, a radar air traffic controller does not need to know an airplane's color to effectively control it. Also, some system states only need to be imprecisely understood. While ATC displays present ground speed to the controller, a two knot ground speed error is not likely to adversely affect the controller's ability to manage aircraft or adversely affect the overall system. Finally, divergence may not lead to negative consequences in all situations. For instance, an aircraft not flying at their clearance altitude is only hazardous when another aircraft or obstacle is in conflict with it. Therefore, this research is concerned with consequential divergence.

Consequential divergence is defined as divergence which is substantial enough in a task relevant state and consequential situation to affect the outcome of the situation. Conversely, *inconsequential divergence* is divergence which is either not substantial enough, not in a task relevant state, or not in a consequential situation to adversely affect the outcome of the situation. For the remainder of this thesis, the term 'divergence' will be used rather than the phrase 'consequential divergence'; the 'consequential' will be assumed.

To clarify the divergence definition, *state* will be defined as a set of variables used to describe a dynamic system as a function of time. State could be considered a vector, $x_i(t), i = 1, \dots, n$, with n variables. As described earlier, not all state variables are relevant. The *task relevant state* will be defined as a subset of the total state vector relevant for the human's particular task. Furthermore, a *consequential situation* will be defined as a situation which could have a reasonable chance of leading to a hazardous consequence.

Divergence can also be decomposed into different types depending upon the human's awareness. First, the human may experience *unknown divergence* (Silva, 2016), where the human assumes that their system state awareness is consistent with the actual system state, but it is not. The human may also experience *known divergence* (Silva, 2016), where the human has awareness that their assumed system state is *not* consistent with the actual system state. When humans experience unknown divergence, they will make decisions and execute actions based on inconsistent state awareness. However, when they experience known divergence, they may make decisions and execute actions to resolve their divergence and re-converge. *Re-convergence* is where the human has been diverged but has since aligned their system state awareness with the actual system state (Silva, 2016).

1.2 Motivation

Many recent aircraft accidents involve divergence between the aircrew state awareness and the actual system state (Silva, 2016). While Silva's work centered on pilot auto-throttle mode confusion and sought to understand divergence in a historical context, a recent Performance-based operations Aviation Rulemaking Committee (PARC)/Commercial Aviation Safety Team (CAST) Flight Deck Automation Working Group (WG) report highlighted areas of concern within the ATC community regarding inconsistent awareness. The report suggested areas of vulnerabilities with human error and misunderstanding, including communication and coordination between pilots and air traffic services, Standard Operating Procedures (SOP), and air traffic service personnel's knowledge of aircraft capabilities (Performance-based operations Aviation Rulemaking Committee/Commercail Aviation Safety Team Flight Deck Automation Working Group, 2013). While divergence between controllers and pilots has likely existed since the inception of the NAS, Silva's work had yet to be extended to the ATC domain with a formal investigation of controller divergence.

The NAS is currently undergoing a unique change which will affect the relationship between pilots and controllers, the addition of UAS. There is an emerging need for UAS integration in the NAS. The global market for UAS is forecasted to grow substantially in the coming years, shown in Figure 1-1, with North America forecasted to occupy 32 percent of the military market (PRNewswire, 2017) and the US to source some 60 percent of the total market (COTS Journal, 2017).

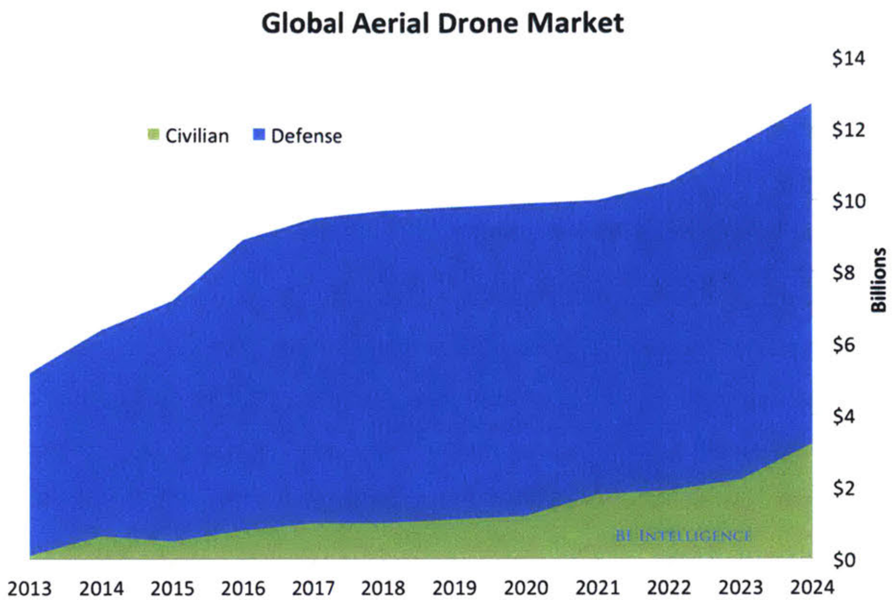


Figure 1-1. Global Aerial Drone Market (BI Intelligence, 2016).

Not only is the UAS market projection driving the need for integration, the Federal Aviation Administration (FAA) Modernization and Reform Act of 2012 mandated federal agencies to develop a comprehensive plan to employ UAS in the NAS within 270 days (House of Representatives, 2012), leading to the UAS Comprehensive Plan (Joint Planning and Development Office, 2013). The inevitable increase of UAS operations in the NAS provides an opportunity to analyze and potentially mitigate controller divergence.

This analysis is vital because the current NAS is designed around manned aircraft (Joint Planning and Development Office, 2012), which are different than Unmanned Aircraft (UA). The differences between manned and unmanned aircraft may increase the likelihood of divergence among controllers managing UAS in the NAS. In fact, many federal agencies and researchers have shown human-system integration concerns with UAS. These concerns include communication and control links, contingency procedures associated with these links, such as lost link (FAA, 2012; Federal Aviation Administration, 2013; Comstock Jr., McAdaragh, Ghatas, Burdette, & Trujillo, 2014; Yuan & Histon, 2014),[1] UAS interaction with the Air Traffic Management (ATM) system (FAA, 2012), and operator sensory differences (Federal Aviation Administration, 2013). Therefore, understanding controller divergence may help inform UAS-integrated NAS procedures and architectures to reduce the likelihood and consequences of controller divergence before UAS-integration occurs.

[1] Lost link is defined as "an interruption or loss of the control link, or when the pilot is unable to effect control of the aircraft and, as a result, the UA will perform a predictable or planned maneuver. Loss of command and control link between the Control Station and the aircraft" (Federal Aviation Administration, 2015).

1.3 Research Objective, Scope, and Focus

The overall objective of this research is to understand divergence and its consequences in human controllers while they manage a human-integrated system and how to minimize them. To accomplish this objective, the research examined the causes of divergence in a human-integrated system and how that divergence became consequential. This examination provided insight for design mitigations to reduce or eliminate the causes of divergence and the factors contributing to its consequential nature.

1.3.1 Scope: Air Traffic Controller Divergence Controlling Manned and Unmanned Aircraft

The ATC domain is characterized by the management of multiple spatially-separated agents requiring the comprehension of states and their projection into the future to accomplish the human agent's goals, primarily safety. This management is predominantly accomplished by an air traffic controller, a human agent that perceives system observables and affects the system by commanding or recommending actions to other system agents. Therefore, there is potential for divergence during the execution of a controller's tasks. While this research is specific to the ATC domain, it is hypothesized to generalize to other domains where humans require state knowledge to manage dynamic situations.

A portion of the research examined case studies, aided by a developed air traffic controller divergence cause and consequence framework and an air traffic controller cognitive process framework. These case studies, all controller-related aviation accidents and incidents, involved only manned aircraft. However, this research capitalized on the unique opportunity of UAS integration and analyzed a future UAS-integrated NAS before the system is fully developed. By examining this system before fielding, the goal is to provide a framework to influence the design to reduce or eliminate controller divergence or divergence consequentiality.

The research focused on two major aspects of divergence within the ATC domain – the causes of controller divergence and how the divergence becomes consequential in the situation. Additionally, the analysis informed development of mitigations to reduce or eliminate divergence within the system.

1.3.2 Focus: Causes of Divergence

A focus of the research was to examine the causes of controller divergence. Although divergence occurs in human cognitive processes, the cause of the divergence could originate in numerous areas of cognition or from outside the human altogether. The cognitive process framework is based on an Input-Process-Output (IPO) model; a simplified model is shown in Figure 1-2.

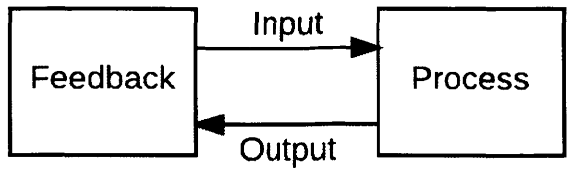


Figure 1-2. Simplified Input-Process-Output model

In Figure 1-2 an incorrect output value could occur from either an incorrect input value to the process or a failure in the processes itself. This research examined the causes of controller divergence using accident and incident case studies leading to hazardous consequences. In addition, it investigated a future UAS-integrated NAS to identify controller opportunities and divergence vulnerabilities.

1.3.3 Focus: Consequences of Divergence

The second research focus was to examine how controller divergence becomes consequential. Divergence becomes consequential when it is substantial in a task relevant state and consequential situation. Specifically, a divergence in the process may not be large enough to lead to an incorrect output or the diverged state may not be required to produce an output. Furthermore, even if the output is incorrect, it may not lead to a hazard in the system.

After investigating controller divergence both in terms of causality and consequentiality, the research identified areas of divergence mitigations. Divergence can be mitigated in the ATC system in two basic ways. Divergence can either be reduced or eliminated *prior* to its occurrence, or the consequences of divergence can be reduced or eliminated *once it has occurred.* Divergence mitigations may be in the form of hardware or software designs, increased communications, or new SOP. Regardless, mitigations should target the diverged state and the process leading to its assessment.

1.4 Research Approach

To accomplish the overall objective, this research was informed by prior work on risk analysis to develop an air traffic controller divergence cause and consequence framework. To better understand the causes and cognitive consequences of controller divergence, this research was informed by prior work on human cognition to develop an air traffic controller cognitive process framework. Next, this research used the frameworks to examine controller divergence in historical case studies of ATC accidents and incidents. Case studies were examined to refine the frameworks, understand the causes and consequence of controller divergence, and provide insight to propose mitigations to reduce or eliminate controller divergence or divergence consequentiality in ATC. Finally, if the causes and consequences of controller divergence are understood early in the implementation of major changes to the NAS, insight gained can be used to reduce or eliminate the causes and consequences of controller divergence, with the goal of reducing or eliminating hazardous consequences. Therefore, to demonstrate the utility of the frameworks, a potential future operating system and environment was analyzed for controller opportunities and divergence vulnerabilities. This research used an UAS-integrated NAS as an example future system to accomplish the task. Table 1-1 below summarizes this approach.

Table 1-1. Research approach overview.

	Divergence Causes	**Divergence Consequences**
Theory	• Divergence Cause and Consequence Framework • Cognitive Process Framework	• Divergence Cause and Consequence Framework • Cognitive Process Framework
Historical Context	• Accident/Incident Case Studies	• Accident/Incident Case Studies
Future Context	• UAS-Integrated NAS	• UAS-Integrated NAS

Specifically, research objectives corresponding to the approach outlined in Table 1-1 are the following:

Objective 1. Develop a framework to help identify causes and consequences of divergence in air traffic controller cognitive processes and controller-system integration.

Objective 2. Utilize the air traffic controller divergence cause and consequence framework and air traffic controller cognitive process framework as tools to understand causes of air traffic controller divergence in air traffic control accident and incident case studies.

Objective 3. Utilize the air traffic controller divergence cause and consequence framework and air traffic controller cognitive process framework as tools to understand consequences of air traffic controller divergence in air traffic control accident and incident case studies.

Objective 4. Utilize the air traffic controller divergence cause and consequence framework and air traffic controller cognitive process framework as tools to identify controller opportunities and divergence vulnerabilities within a UAS-integrated NAS.

Using this approach, the research developed insight into controller divergence from a human-integrated systems perspective. This approach provided understanding of both the cognitive capabilities and limitations of the human controller and the system capabilities and limitations which can affect human divergence. With this understanding, effective mitigations can be targeted at critical system deficiencies or transformable human limitations.

2 Air Traffic Control System

To minimize divergence and its consequences in human controllers while they manage a human-integrated system, it is important to understand the system's operational context and the air traffic controller's task.[2] The ATC system's primary purpose is to prevent a collision between aircraft operating in the system and to provide a safe, orderly, and expeditious flow of traffic (Federal Aviation Administration, 2015). The system also has the capability to provide additional services based on traffic volume, frequency congestion, radar quality, controller workload, duty priorities, and other human limitations (Federal Aviation Administration, 2015). The FAA created this system to protect passengers and crew, persons and property on the ground and to establish a safe and efficient airspace environment for civil, commercial, and military aviation (Federal Aviation Administration, 2007). To accomplish the ATC system's purpose, controllers must be converged in their task relevant states. This chapter will present background on the NAS, ATC, and UAS.

2.1 National Airspace System

To aid in accomplishing the ATC system's purpose, the FAA has developed a NAS with multiple layers of structure. The NAS is a network of air navigation facilities, ATC facilities, airports, technology, and appropriate rules and regulations needed to operate the system (Federal Aviation Administration, 2007). This structure assists the controller managing the system in many ways, particularly for this thesis, by helping the controller remain converged with the system.[3]

To begin, weather conditions constrain the flight rules under which aircraft can operate and also affect aircraft separation standards (i.e. the distance allowed between aircraft during flight).[4] Aircraft operate under two distinct categories of operational flight rules: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). These two flight rules are linked to two categories of weather conditions: Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC). During VMC aircraft *may* operate under VFR, during which the pilot is primarily responsible for seeing other aircraft and maintaining safe separation. During IMC aircraft *must* operate under IFR where ATC exercises control and separates all air traffic via verbal or data commands. Aircraft *may* elect to operate IFR in VMC, but the pilot still has the final responsible for seeing and avoiding other aircraft (Federal Aviation Administration, 2007). The Code of Federal Regulations (CFR) provides the rules for pilots providing their own aircraft separation. Regulations state "vigilance shall be maintained by each person operating an

[2] For a comprehensive review of the ATC system, see Nolan's *Fundamentals of Air Traffic Control* (Nolan, 2010).
[3] Structure's importance in ATC is discussed in 3.1 Human Information Processing with research by Histon (2008).
[4] Required aircraft separation is dependent on weather conditions, flight rules, class of airspace, aircraft capabilities, and type and distance of the radar facility to the aircraft (Nolan, 2010). The goal is to provide efficiency while maintaining the appropriately level of safety.

aircraft so as to see and avoid other aircraft" (Code of Federal Regulations, 2016) and "no person may operate an aircraft so close to another aircraft as to create a collision hazard" (Code of Federal Regulations, 2016).

In addition to tactical ATC services, IFR aircraft must file a flight plan with the FAA and receive a clearance from an ATC facility. VFR aircraft are allowed, but not required, to file a flight plan as well. The flight plan provides ATC information to help manage air traffic in the NAS, such as the type of flight plan (VFR or IFR), aircraft identification number, aircraft type and navigation equipment installed, departure point, departure time, cruising airspeed, cruising altitude, requested flight route, destination airport, and additional information (Nolan, 2010). Next, an IFR aircraft must be issued an ATC clearance prior to beginning their IFR flight, including information such as their clearance limit (farthest location to which the aircraft is cleared), departure procedure, flight route, altitude assignment, and additional information (Nolan, 2010). While clearances can be amended in flight by the controller, they provide the controller with an expectation of the future aircraft trajectory during flight, important for convergence of their future state awareness and the actual system state. In addition to the categorization of IFR and VFR aircraft operations, airspace class determines different procedures for the controller and pilot.

The FAA has designated six classes of airspace in accordance with International Civil Aviation Organization (ICAO) guidance. Designating airspace classes, with different procedural and equipage requirements, provides user flexibility while maintaining the required level of safety (Nolan, 2010). Airspace is defined using four general categories. First, *positive controlled airspace* is one which ATC separates all aircraft (Nolan, 2010). In the US, the FAA has designated this airspace as Class A. Typically VFR aircraft are prohibited from accessing this airspace. On occasions when VFR aircraft are permitted access, ATC continues to exercise positive control over all aircraft, including VFR aircraft. Second, *controlled airspace* is one where ATC separates all IFR aircraft from other IFR aircraft, but not necessarily VFR aircraft. VFR aircraft are permitted access to the airspace, weather permitting, but provide their own separation from IFR and other VFR aircraft (Nolan, 2010). In the US, this airspace is Class B, C, D, and E. Here, IFR aircraft are permitted to fly through clouds, while VFR aircraft must remain specified distances away from such weather. Class B, C, and D airspace are typically located at and around airports with operating control towers. In addition, in some Class E airspace VFR aircraft are permitted operation without contacting ATC, highlighting the importance of the see-and-avoid principle defined in the CFRs. Third, *uncontrolled airspace* is one which the pilots provide all aircraft and terrain separation and ATC separation services are not provided, regardless of IFR or VFR operations (Nolan, 2010). In the US, Class G is uncontrolled airspace. Fourth, *Special Use Airspace (SUA)* has special operating restrictions and rules, differentiated completely from the other three airspace types. Some SUA, such as *prohibited* airspace is restricted from use regardless of aircraft type, and the pilot and ATC (when appropriate) share responsibility to avoid these areas. Other SUA, such as *Military Operations Areas (MOAs)* are restricted from use for IFR aircraft when active, but VFR aircraft are permitted to enter without clearance. A typical depiction of US airspace is shown in Figure 2-1 and presents the cross-section of airspace with respect to altitude. Here, AGL refers to Above Ground Level while MSL refers to Mean Sea Level. Also, FL refers to Flight Level and is used in the US when above 18,000 feet MSL. After this value, altitude is described in Flight Levels in 100 foot increments. FL190 refers to 19,000 feet MSL using a standard reference setting for pressure of 29.92 inches of mercury. Therefore, US Class A airspace is the block from 18,000 feet MSL to FL600 as shown.

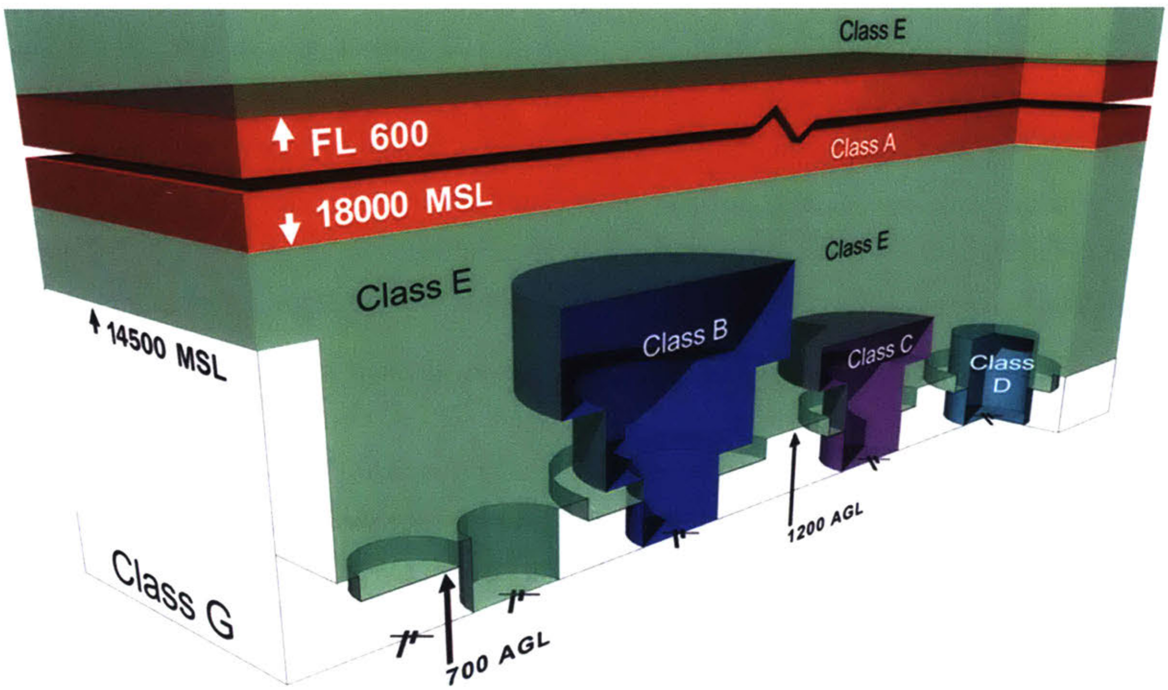


Figure 2-1. Airspace depiction.

2.2 Air Traffic Control

To provide ATC services for the NAS, the FAA has developed a system of facilities, procedures, and personnel. This system provides structure to pilots and controllers to provide safe NAS operations.

2.2.1 Air Traffic Control Facilities

The highest level of decomposition within the US NAS is the Air Route Traffic Control Center (ARTCC). The FAA has divided the NAS into 22 ARTCCs, with the 20 ARTCCs of the Continental US (CONUS) shown in Figure 2-2. The basic function of the ARTCC is to separate aircraft traveling between airports, or while enroute (Nolan, 2010). However, controllers in an ARTCC also provide services for aircraft climbing to and descending from their cruising altitude. In remote areas, they may provide approach and departure services to small tower-controlled or uncontrolled airports.

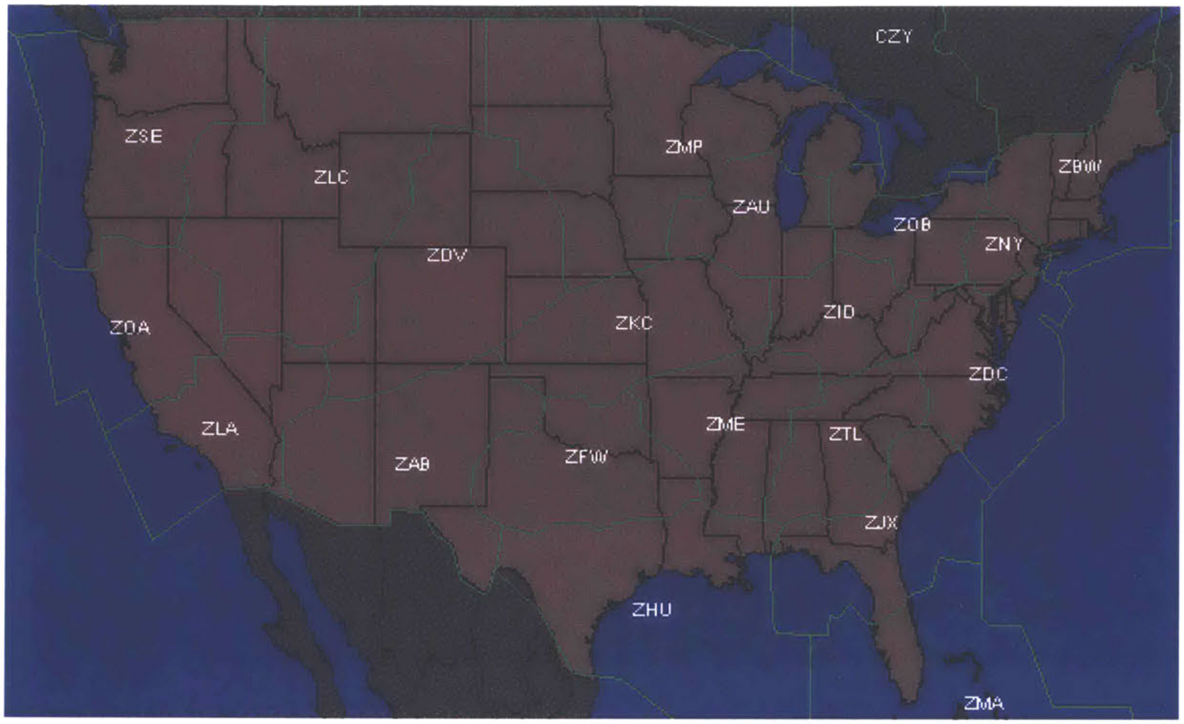


Figure 2-2. NAS ARTCC facilities (VATSIM Cleveland ARTCC, 2017).

If the FAA determines that safety and efficiency would be increased if a smaller facility were responsible for a given piece of airspace, an ARTCC may delegate aircraft separation responsibility to that facility.

For airspace surrounding many major airports, radar services may be available for departing and arriving aircraft and the FAA facility is referred to as a Terminal Radar Approach Control (TRACON) or Radar Approach Control (RAPCON) for a military facility. The basic function of the TRACON or RAPCON is to provide separation for aircraft through the sequencing and merging of arriving traffic to an airport or the managing of departing aircraft while climbing to their enroute cruise altitude. A depiction of CONUS terminal airspace is shown in Figure 2-3.

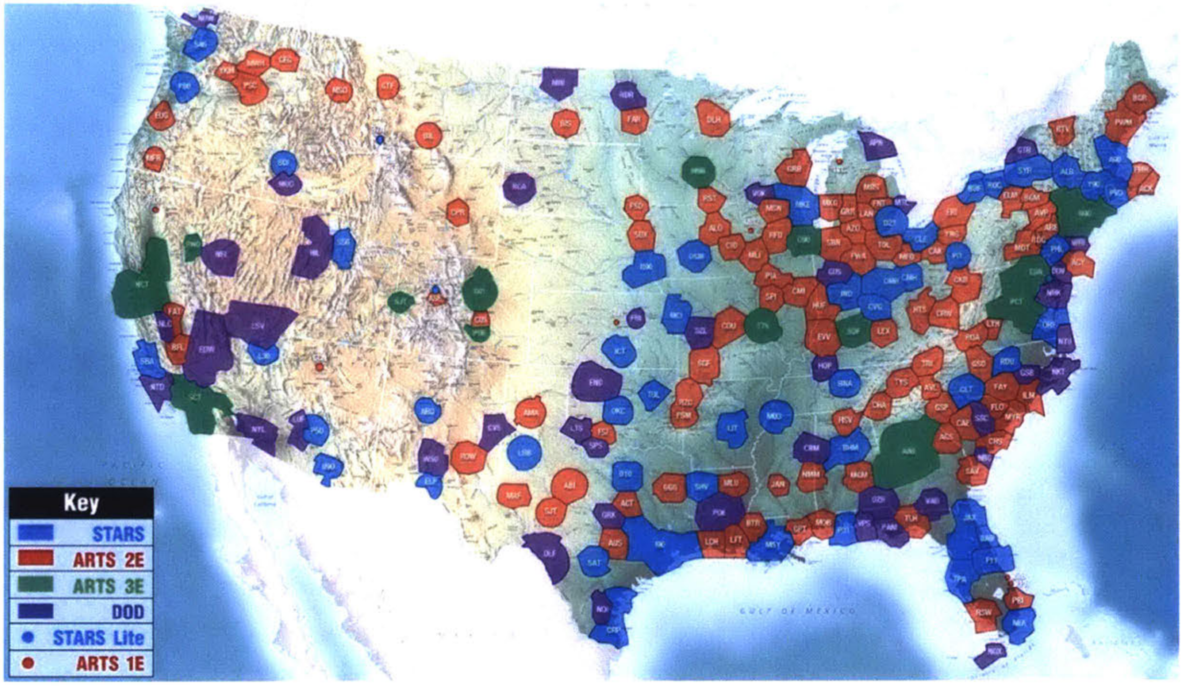


Figure 2-3. NAS TRACON and RAPCON facilities (North America Region Training Academy, 2017).

For airspace in the immediate vicinity of an airport, the FAA facility is referred to as an ATC Tower (ATCT) whose primary responsibility is to ensure sufficient runway separation between aircraft landing and departing (Nolan, 2010). In the US, many smaller airports are non-towered and uncontrolled, and no ATC services are provided but pilots communicate on a Common Traffic Advisory Frequency (CTAF).

A typical flight profile of an aircraft flying from one airport to another is generically shown in Figure 2-4. For example, an aircraft could takeoff from an airport in Class B airspace while communicating with an ATCT, then transfers communication to a TRACON facility during its climb to cruising altitude. Prior to reaching cruise altitude, the aircraft may be handed off to an ARTCC for communication enroute in Class A airspace. When nearing its destination, the aircraft may descend into Class E airspace and transfer communication to another TRACON facility. Finally, the aircraft may enter Class C airspace nearing the airport, and after transitioning to final approach be switched to ATCT for landing.

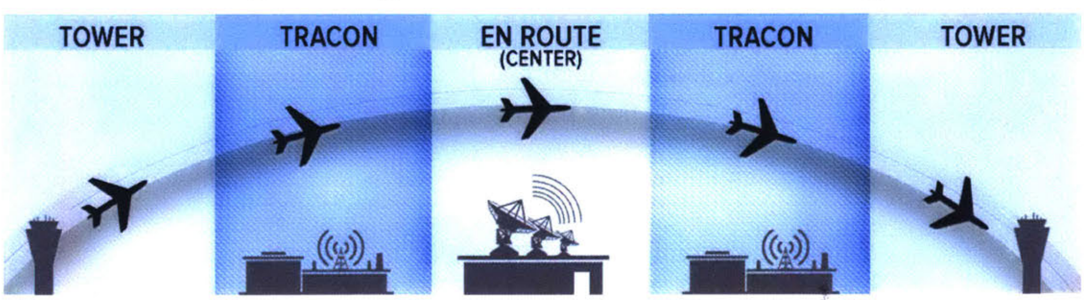


Figure 2-4. Typical flight profile (Aviation Stack Exchange, 2017).

2.2.2 Air Traffic Controller Division of Labor

Due to the vast size of an ARTCC, these areas are divided into *sectors*. Sectors have lateral and vertical boundaries which vary in shape, size, and altitude (Histon, 2008). Depending on the size, complexity, or congestion of a sector, it may have a single controller or a team of controllers to manage aircraft within it. The controller directly communicating with the aircraft is the *radar controller*, responsible for issuing altitude, heading, or airspeed changes to ensure separation between participating aircraft. The sector may also be staffed with a *radar associate/nonradar controller* whose duties are to assist the radar controller when separating aircraft that do not appear on the radar display and updating the Flight Progress Strips (FPS) to accurately reflect aircraft position, altitude, and route of flight (Nolan, 2010). A sector may include a *flight data controller*, who assists in coordination between controllers and other agencies.

Inside TRACON and RAPCON facilities, the primary division of labor is similar to controllers in ARTCCs. *Approach control* and *departure control* positions are usually designated and could vary in number from a single controller to forty controllers depending upon congestion within the airspace (Nolan, 2010). Similar to ARTCCs, TRACON and RAPCON facilities are similarly equipped with radar to provide separation services for participating aircraft.

Inside ATCT facilities, the division of labor is different from ARTCC or TRACON facilities. The *local controller* is primarily responsible for aircraft separation within the airport traffic area and taking off or landing on the airport's active runways (Nolan, 2010). At busy airports, this position may be separated into two or three controllers, each tasked with controlling different runways for takeoff or landing. For ground operations not on active runways, a *ground controller* is responsible for aircraft separation and taxiing vehicles (Nolan, 2010), which also may be separated at busy airports. In addition, other controllers may be assisting, supervising, or managing controllers or coordinating within and between facilities.

2.2.3 Air Traffic Control Tasks

To provide the services required controllers must perform a number of tasks during routine operations. As an example, a cognitive task analysis of a radar enroute controller (ARTCC controller) determined the controller's primary tasks to be the following (Seamster, Redding, Cannon, Ryder, & Purcell, 1993):

- Maintain situation awareness
- Develop and revise sector control plan
- Resolve aircraft conflict
- Reroute aircraft
- Manage arrivals
- Manage departures
- Manage overflights
- Receive handoff
- Receive pointout
- Initiate handoff
- Initiate pointout
- Issue advisory
- Issue safety alert

This thesis focuses on a subset of the first task, "maintain situation awareness," which corresponds to controller state awareness. However, this task is often a prerequisite to other tasks on the list. Conversely, the other tasks controllers perform may provide insight into their state awareness.

While TRACON controllers specialize in sequencing aircraft into the airport from the enroute environment or transitioning aircraft from the airport to the enroute environment, their tasks are largely the same as ARTCC controllers' tasks. However, control within the ATCT differs considerably from the radar environment. According to Nolan, local controllers (Nolan, 2010):

- Determine the active runway
- Issue landing and takeoff clearances
- Issue landing information
- Sequence landing aircraft
- Coordinate with other controllers
- Issue weather and Notices To Airmen (NOTAM) information to pilots
- Operate the runway and approach lighting system

In addition, tower control primarily involves sequencing aircraft rather than providing separation, the latter is usually accomplished by pilots. However, state awareness requirements exist for all controllers depending on their current task. They receive much of their state awareness by inputs from the system, particularly at their control stations.

2.2.4 Air Traffic Control Stations and Structure

Controllers receive various inputs to accomplish their tasks. While tower controllers are able to perceive the system directly (looking out of the tower cab window), TRACON and ARTCC controllers must rely on a system of sensors, displays, and other controllers to perceive required information for task accomplishment. Under radar control, controllers provide separation services primarily using a Traffic Situation Display (TSD), which displays primary or secondary radar returns to a display screen. Non-radar controllers must use other means to gain aircraft position awareness for separation. Although all controllers utilize FPS, these prove invaluable for non-radar controllers to maintain awareness and provide separation. FPS are standardized strips of paper (electronic versions exists) displaying aircraft clearance, but which controllers mark to provide a visual representation of the most current clearance or other notes.

When ATC services are used, the primary medium for coordination between pilots and controllers is verbal communication. This communication has traditionally been conducted using radio communications with each controller assigned one or more frequencies to communicate with aircraft within their area of responsibility. Controllers have access to telephones to coordinate with other controllers within and between facilities. To ensure accurate understanding and brevity, communications procedures are rigidly structured. To reduce communication congestion and misunderstanding the use of Controller-Pilot Data Link Communications (CPDLC), a means of non-verbal communication between pilots and controllers, is being expanded into the tower and enroute environment (Federal Aviation Administration, 2017). In addition to structured communications, both the NAS and ATC system are characterized by structured procedures. Navigation and separation in the NAS are dependent upon pilots and controllers abiding by specified procedures during all phases of flight. During VFR operations, procedures for altitude during cruise flight, pattern procedures within the vicinity of airports, and right-of-way rules have been established. During IFR operations, procedures are more restrictive, with aircraft following specific ground-based or satellite-based navigational routes, controller instructions and clearances, and coordinated plans during normal and contingency operations. This allows for the controllers to better project future aircraft position and crew actions to accomplish their purpose, maintaining NAS safety.

2.3 Unmanned Aircraft Systems Background

An unmanned aircraft is simply an aircraft with its aircrew removed from the onboard cockpit and replaced by a computer system and radio-link. More formally, the FAA has defined UAS as "an unmanned aircraft and its associated elements related to safe operations, which may include control stations (ground, ship, or air-based), control links, support equipment, payloads, flight termination systems, and launch/recovery equipment" (Federal Aviation Administration, 2013). For the purposes of this research, an UAS will be decomposed into the following distinct elements.

2.3.1 Unmanned Aircraft System Elements

An UAS consists of five distinct elements as follows: An Unmanned Aircraft (UA), Control Station (CS), UAS Operator (UASO), control link, and communication link. A visual representation of the elements can be seen in Figure 2-5.

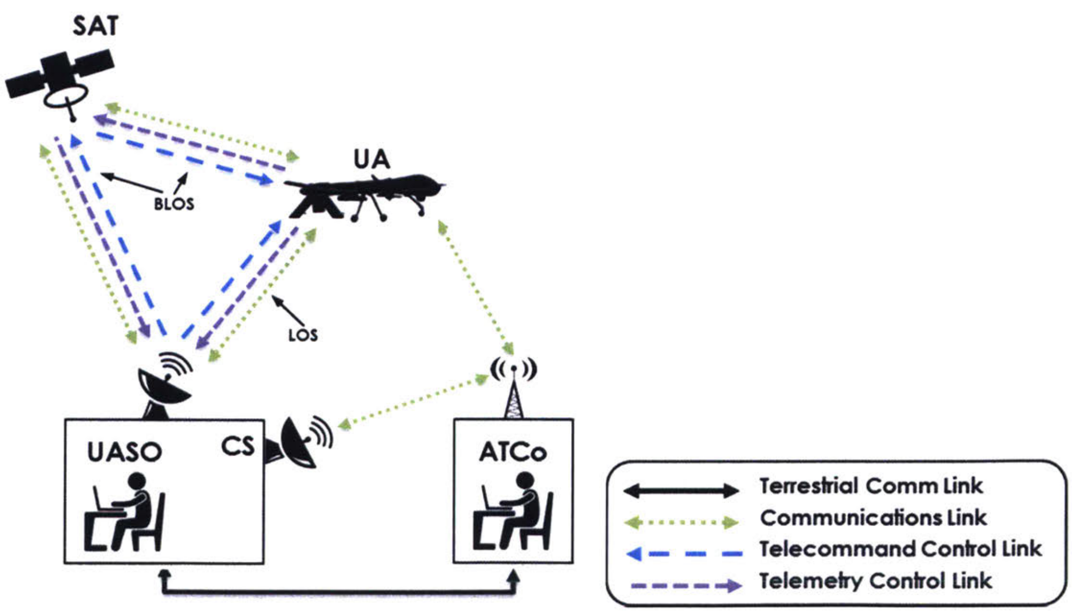
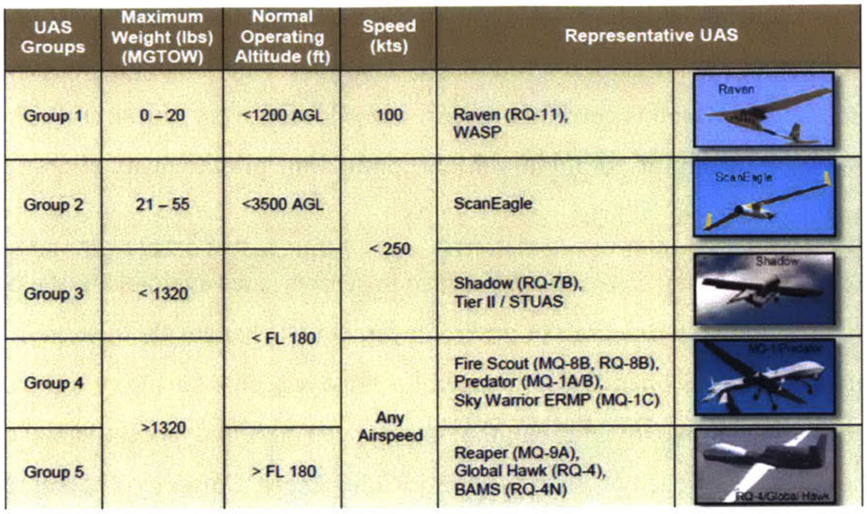


Figure 2-5. UAS architectural elements.

The UA element is a device used or intended to be used for flight in the air that has no onboard pilot (Federal Aviation Administration, 2013), analogous to a Manned Aircraft (MA) with respect to the numerous systems (e.g. flight controls, navigation, etc.) required to operate in the NAS. The CS is the equipment necessary to operate an UA (Federal Aviation Administration, 2013), analogous to a cockpit in a MA. The UASO operates the UA from inside the CS and is the pilot in command charged with the safe conduct of a flight (ICAO, 2011), analogous to a pilot. Unlike MA, the UASO requires a wireless link to manage the UA. The control links are the data links between the UA and CS for the purposes of managing the flight (ICAO, 2011), which can be decomposed into a telecommand link (up-link) and telemetry link (down-link) as shown in the blue and purple dashed lines of Figure 2-5. The telecommand link sends control commands from the CS to the UA and the telemetry link sends feedback from the UA to the CS. Depending on UAS type, the control links may operate within Line Of Sight (LOS) or Beyond Line Of Sight (BLOS). BLOS control links must pass through an intermediary before reaching a node within LOS of the UA, typically a satellite but can be linked ground nodes. The communication link is the voice or data relay of instructions or information between the UASO and the controller or other NAS users (Federal Aviation Administration, 2013), similar to MA. Communication links may operate in different ways, as shown in green dotted and black solid lines in Figure 2-5. If the CS is close to the ATC facility controlling the UA, then communications may go direct between the CS and ATC facility, bypassing the UA. Or, the communication link may pass through the UA, either LOS or BLOS. Finally, the communication link may pass through a terrestrial line from the CS to the ATC facility.

2.3.2 Unmanned Aircraft System Categorization

UAS are a broad category and usually decomposed by the capability or size of the aircraft, yet the boundaries between categories are often blurred. The Department of Defense (DoD) categorization is shown in Figure 2-6 (Department of Defense, 2011).



UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (ft)	Speed (kts)	Representative UAS
Group 1	0 – 20	<1200 AGL	100	Raven (RQ-11), WASP
Group 2	21 – 55	<3500 AGL	< 250	ScanEagle
Group 3	< 1320	< FL 180		Shadow (RQ-7B), Tier II / STUAS
Group 4	>1320		Any Airspeed	Fire Scout (MQ-8B, RQ-8B), Predator (MQ-1A/B), Sky Warrior ERMP (MQ-1C)
Group 5		> FL 180		Reaper (MQ-9A), Global Hawk (RQ-4), BAMS (RQ-4N)

Figure 2-6. DoD UAS group descriptions (Department of Defense, 2011).

The FAA has categorized small UAS operations under Part 107 of the CFR (Code of Federal Regulations, 2017), where the UA must weigh less than 55 pounds and flown within Visual Line-Of-Sight (VLOS) below 400 feet AGL. The FAA and National Aeronautics and Space Administration (NASA) are researching low altitude airspace allocation to UAS via UTM (UAS Traffic Management) (NASA, 2015). However, this thesis is scoped to UAS integrated within controlled airspace and managed by controllers similarly to MA, typically Group 3 to 5 in Figure 2-6 whose characteristics are described next.

2.3.3 Unmanned Aircraft System Characteristics

The primary characteristic differentiating UAS from MA is the location of the operator, which changes the system in many ways. If the system desires operator input during flight, a wireless link is required between the UASO and the UA for aircraft control. With this architecture, UAS control links are likely more vulnerable than their manned counterparts (Lacher, et al., 2010; US Department of Transportation, 2014). Lost and faded links can be caused by a number of issues, such as equipment failure (Austin, 2010; Neale & Colin, 2015), human error (Neale & Colin, 2015), Radio Frequency (RF) multi-path (Neale & Colin, 2015), weather interference (Petranovich, 2016; VantagePoint, 2016), terrestrial blockage (Austin, 2010; VantagePoint, 2016), pilot maneuvering, and airframe blanking. If the duration of the control link loss exceeds established requirements, a *lost link* has occurred. Lost Link (LL) is defined as an interruption or loss of the control link, or when the pilot is unable to effect control of the aircraft (FAA, 2012). To mitigate the consequences when a LL occurs, UA are normally designed to execute an automated LL procedure to either attempt to re-establish the control link connectivity or otherwise safely conclude the UA flight.

The lack of an onboard pilot combined with the design of automated LL procedures highlights the opportunity for different control architectures and automation available for UA. For example, while UAS operations currently include an operator with the ability to maneuver the aircraft real-time (FAA, 2012; Federal Aviation Administration, 2013), the technology is available for changing the current paradigm of the ratio of pilots to aircraft, which is currently at least one pilot for every one aircraft. Fully autonomous operations, zero pilots to one aircraft, or multi-vehicle control, one pilot to many aircraft, are potential control architectures (Cummings, 2004).

Another significant change among UA is the difference in sensory cues available to the operator. The UASO cannot directly perceive the aircraft or environment, which changes the system in a variety of ways. Without fully autonomous operations, the operator must rely on a telemetry link with displays for aircraft control as described above. In addition, the operator can no longer accept visual clearances from the controller, either visual approach or visual separation clearances. Currently, federal regulations state that "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft" (Code of Federal Regulations, 2016) and "no person may operate an aircraft so close to another aircraft as to create a collision hazard" (Code of Federal Regulations, 2016). Yet UASO cannot fulfill the see-and-avoid regulatory requirements using traditional methods, namely the pilot's vision. UAS must ensure they remain 'well clear' of not only airborne traffic, but also ground obstacles and weather hazards. This may require technology to provide a means for 'self-separation' and collision avoidance (FAA, 2012). *Self-separation* is analogous to the requirements for manned aircraft to remain well clear of other aircraft. In addition, collision avoidance technology may be required to provide similar performance as currently fielded Airborne Collision Avoidance Systems (ACAS) on manned aircraft, such as TCAS (Traffic Collision Avoidance System).

2.3.4 Unmanned Aircraft System Integration Challenges from Literature

Prior work on UAS-integration in the NAS has revealed multiple challenges based in part on characteristics described above. Although a LL procedure is a mitigation of wireless control link vulnerability to disruption or loss, many federal agencies and researchers have shown human-system integration concerns with UAS contingency procedures. These concerns include delayed controller notification of a LL state (FAA, 2012), consistent and predictable UA responses following LL (FAA, 2012; Federal Aviation Administration, 2013; Comstock Jr., McAdaragh, Ghatas, Burdette, & Trujillo, 2014; Yuan & Histon, 2014), and integration of LL procedures in ATC automation systems (FAA, 2012).

Using surveys of controllers, manned aircraft pilots, and UASOs, Yuan and Histon determined information required for each agent to safely integrate UAS in the NAS (Yuan & Histon, 2014). Among their many findings they described the variety of control architectures that could lead to different behaviors of different UAS types. Some could behave similarly to manned aircraft, while others may need to be treated similarly to birds, weather, or other non-controllable objects. Indeed, differences in the control architecture from fully autonomous aircraft to UASOs controlling multiple UAS may exacerbate the non-controllability of UAS in the future (Yuan & Histon, 2014).

In addition to control architectures, Yuan and Histon found controllers' most often cited new information requirement was UAS Sense-And-Avoid (SAA) capability.[5] Also using surveys of controllers, Comstock et al. (2014) found that controllers require whether an aircraft is manned or unmanned through symbology or data-tag information for multiple reasons. One reason is their inability to see-and-avoid, information a controller needs to make decisions regarding traffic calls, separation, and sequencing (Comstock Jr., McAdaragh, Ghatas, Burdette, & Trujillo, 2014). The FAA cited ATC challenges to include see-and-avoid responsibilities in their integration roadmap (Federal Aviation Administration, 2013), while the FAA's Concept of Operations (CONOPS) for UAS suggests technology-based separation such as delegated separation (FAA, 2012), similar to the Next Generation Air Transportation System (NextGen) concept of Equivalent Visual Operations (EVO), where aircraft self-separate using technology such as Automatic Dependent Surveillance-Broadcast (ADS-B) instead of vision (Simons, DeSenti, Estes, & Hawkins, 2005; Domino, Tuomey, Mundra, & Smith, 2010; Domino, Tuomey, Mundra, Smith, & Stassen, 2011; Prinzel III, et al., 2011; Kenny, 2013), as a possible mitigation to see-and-avoid concerns.

Due to design considerations such as mission goals and development factors, UA have proven vulnerable to inclement weather thus far in their use (Rabe, Abel, & Hansman, 2016). As of 2013 the largest issue with UAS in the DoD remained the inability to operate in bad weather (Department of Defense, 2013). A Government Accounting Office (GAO) report stated UAS are more likely to be grounded in inclement weather than manned aircraft (GAO, 2005), specifically regarding wake vortex and other turbulence along with airframe icing. This weather susceptibility may be due to their lighter weight structures, small airframes, and high-aspect ratio wings (Rabe, Abel, & Hansman, 2016). The FAA highlighted unmanned aircraft's susceptibility to wake vortex and other turbulence due to their unique characteristics (Federal Aviation Administration, 2013). Many UA are designed to maintain a steady flight path for their payload sensors, using large aerodynamic surface areas and high aspect ratio wings to do so (Austin, 2010). However, this increases the response when turbulence is encountered. In addition to turbulence, airframe icing poses a challenge for UAS operations. Ice accumulation on UA is a common problem (Nelson, 2017), causing a number of accidents (GAO, 2005). Turbulence, airframe icing, and high winds are less detectable by the UASO due to their lack of sensory cues (Rabe, Abel, & Hansman, 2016). In addition, the possibility of LL increases the risk because the LL procedure may include unplanned weather penetration.

[5] Sense-And-Avoid (SAA) is a function to act in the place of a human pilot to detect and resolve certain hazards to safe flight, consisting of other traffic or objects presenting a risk of collision (Angelov, 2012).

3 Literature Review

A literature review was conducted to understand current knowledge relevant to the field of divergence. Previous work conducted initial divergence explorations focusing on pilot divergence with auto-throttle systems (Silva & Hansman, 2015; Silva, 2016). To expand this concept and better understand how to minimize divergence in other domains, a review of current literature focusing on the causes and consequences of divergence was conducted. To model the mechanisms contributing to divergence to better understand its causes and how to reduce or eliminate them, Human Information Processing (HIP), Situation Awareness (SA), and human error literature was reviewed. Human state awareness is formed by HIP mechanisms. Current descriptive methods to model and decompose cognitive processes were reviewed to understand the individual mechanisms affecting human state awareness. State awareness has been cited as a subset of SA (Silva, 2016), and models from Histon and Endsley formed the basis of a cognitive process framework proposed to investigate divergence in this research due to their comprehensiveness and relevance to the domain scope. Divergence was proposed to occur from cognitive process failures (Silva, 2016); therefore, human error literature was reviewed to understand factors affecting divergence causality.

To understand the consequences of divergence and to identify design mitigations to minimize its effects, HIP, human error, and risk analysis literature was reviewed. HIP was reviewed to understand the cognitive consequences and subsequent actions once divergence has occurred. This review included human error research other than divergence to elucidate cognitive errors post divergence and error effects other than divergence within a system. Also, risk analysis models have attempted to describe effects of error in complex systems. Risk analysis literature was reviewed to understand and document how divergence and other error affect a system, possibly leading to undesirable consequences. This review will provide the basis for techniques proposed to understand divergence in previous accidents and incidents and to propose mitigations to prevent divergence and its consequences in future systems.

3.1 Human Information Processing

This research is grounded in analyzing HIP using descriptive modeling to understand the cognitive mechanisms causing divergence as well as the consequences of divergence once it has occurred. This research views human cognitive behavior through an IPO model and decomposes various processes of cognition to describe the information flows between them. HIP research and models have been influenced by information theory, control theory, and computer science, but much of the approach developing and organizing cognitive subsystems stems from experimental human performance studies (Proctor & Van Zandt, 2008). In Figure 3-1, Proctor and Van Zandt illustrated a simplified model of information processing that delineates HIP into three main processes: perception, cognition, and action (Proctor &

Van Zandt, 2008). Perception describes the process of gathering information from the stimulation of the sensory organs. In ATC activities, humans perceive environmental cues primarily through vision and hearing. Perception also includes the beginning stages of information processing to identify and classify the stimulus. Perception is critical to prevent divergence, where sensory inputs provide cues updating the human's awareness. Next, information flows from perception to cognition to determine an appropriate response. This process may include retrieving knowledge from memory, comparing or matching information with other information, and decision making. Finally, information flows to action to execute the chosen plan.

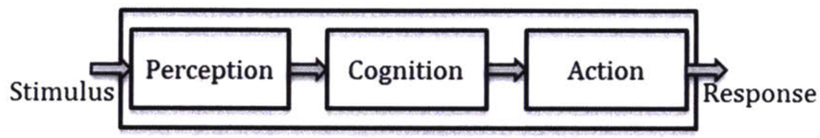


Figure 3-1. Three stages of information processing, adapted from (Proctor & Van Zandt, 2008).

To capture mechanisms contributing to awareness and error, a more detailed HIP model is required. Adapted from Wickens, Hollands, Banbury, & Parasuraman (2013), Figure 3-2 integrates other limited models, components, and processes commonly agreed upon and mostly substantiated by research to form a larger model of cognition. This model illustrates cognitive mechanisms useful for understanding interactions between various components of cognition. It adds the concept of a short-term sensory store, which may hold sensed information for up to one second (Wickens, Hollands, Banbury, & Parasuraman, 2013).

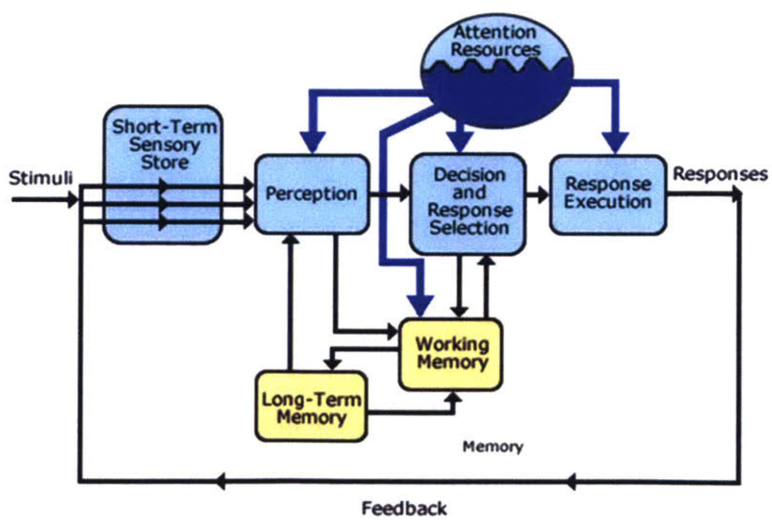


Figure 3-2. Wickens, Hollands, Banbury, & Parasuraman (2013) model of human information processing as in (FAA, 2016).

In addition, the model incorporates both long-term and working memory. Long-term memory is defined simply as a storehouse of facts about the world and how humans do things (Wickens, Hollands, Banbury,

& Parasuraman, 2013). Long-term memory is primarily used in ATC to accomplish two tasks. *Recall* is the process of being presented with information that must be retrieved later (Wickens, Hollands, Banbury, & Parasuraman, 2013). *Recognition* is the process of determining if certain information was presented in the past (Wickens, Hollands, Banbury, & Parasuraman, 2013). Another decomposition of long-term memory is associated with the type of information stored. *Episodic memory* is the memory of specific events in time, which may or may not be autobiographical (Wickens, Hollands, Banbury, & Parasuraman, 2013). Controllers use episodic memory of their past experiences to inform plans for current situations. *Semantic memory* refers to memory of factual information (Wickens, Hollands, Banbury, & Parasuraman, 2013), such as ATC regulations. *Procedural memory* refers to the memory of using objects with the body (Wickens, Hollands, Banbury, & Parasuraman, 2013), such as using a radio or configuring a display.

Working memory, often used synonymously with short-term memory, is an important component in cognition for controllers. Working memory can be defined as a temporary store used to retain new information (Wickens, Hollands, Banbury, & Parasuraman, 2013). It is hypothesized to also be used as a 'workbench' of thought to examine, evaluate, transform, and compare different mental representations. Controllers may use working memory to perform mental simulation of future scenarios (Proctor & Van Zandt, 2008). During dynamic processes such as ATC, a heavy load is imposed on working memory due to the numerous activities required of it (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). This load can cause memory failures, which occurs when a human forgets a system state, possibly leading to divergence.

Finally, Wickens et al.'s model depicts attentional resources as contributors to numerous cognitive processes. In order for an external stimulus to be perceived and processed, it must be detected by a HIP system. The process of directing the detection of stimuli and distributing the downstream processing of stimuli is referred to as *attention*. Attention can be decomposed into *selective attention*, where attention is directed, *focused attention*, how narrowed is the attention to prevent distraction, *divided attention*, where multiple channels of attention are directed,[6] and *sustained attention*, vigilance maintaining attention (Wickens, Hollands, Banbury, & Parasuraman, 2013). However, as the level of stimuli input and processing requirements increase, the human may need to prioritize and select only a subset of these stimuli for perception and processing (James, 1890). Several models of attention have been proposed, including filter theory, filter-attenuation model, late-selection model, unitary-resource models, and

[6] Initially research viewed the human information processor as a single-channel requiring switching attention from one task to another when multiple tasks were attended to. Research transitioned to viewing attention as a general-purpose resource similar to a computer, applying attention to various tasks until resources are fully allocated. Since 1980, many researches have transitioned to a multiple-resource attention theory divided among three main dimensions (stages of processing, codes of processing, and input/output modalities) (Tsang & Vidulich, 2003).

multiple resource models (Proctor & Van Zandt, 2008).[7] To highlight attention deficiencies and system designs contributing to divergence, this research will model attention as a resource of finite quantity that can be utilized by multiple cognitive processes. As such, attention is hypothesized to be directed to a variety of cognitive sources. In fact, the attention process may decide the stimuli to be processed further based on pattern recognition from both long-term and working memory resources (Pohlman & Fletcher, 2010). Earlier work suggested attention may be guided by four factors (Wickens & Flach, 1988):

- Knowledge: attention is guided by knowledge about the statistical properties of the environment.
- Memory: memory limitations result in a tendency to attend to stimuli more often than needed.
- Planning: a plan of action developed in cognition will focus and direct attention.
- Stress: high stress can restrict the number of cues that are attended to.

Later, additional factors influencing attentional processes were added (Wickens & Carswell, 2006):

- Salience: salient features of the environment will attract or 'capture' attention.
- Effort: attention allocation may be negatively influenced by the effort required to move attention.
- Expectancy: knowledge about the statistical properties of information availability.
- Value: importance of knowing information and the cost of failing to attend to it.

Like any component of cognition, attention allocation is vulnerable to error. Humans must often perceive and comprehend changing information from observables that are not particularly salient; when such changes are not noticed, this lack of perception is called *change blindness* (Rensink, 2002) or *attentional blindness* (Wickens, Lee, Liu, & Gordon Becker, 2004). Limited attentional resources and increasing displayed information can also lead to missed perceptions (Moray N. , 1986). No matter how perceptions are missed they could lead to human divergence.

Although many HIP models prescribe to Wickens et al.'s general mapping, Pawlak, Brinton, Crouch, and Lancaster presented a slightly different model. They argued the mental and physical processes required in ATC are better revealed through analysis of controller strategies and decision-making activities (Pawlak, Brinton, Crouch, & Lancaster, 1996). This research, analyzing decision making activities and their composed strategies, assumed the controller's primary task to maintain separation. Based in four processes, *planning* determines the best course of action to resolve a given situation. Following *implementation* of a plan, a *monitoring* task ensures conformance of the situation (similar to SA) to the plan, while an *evaluation* task measures the plan's effectiveness resolving a conflict in relation to the controller's goals and constraints.

Similarly, Histon developed a cognitive process model for controllers to understand structure's influence on cognitive complexity (Histon, 2008). This model includes key parts of Endsley's model of SA, discussed in 3.2 Situation Awareness, to illustrate how SA supports and influences the controller's decision making processes which were modeled using Pawlak et al.'s model (Pawlak, Brinton, Crouch, &

[7] For an overview of various attention models, see (Proctor & Van Zandt, 2008) pages 230-237.

Lancaster, 1996), to illustrate four key types of decisions made by controllers, discussed earlier. Histon's model is comprehensive, domain specific, and was used as the basis for the cognitive process framework in this research. Using an ethnographic approach to create the model in Figure 3-3, Histon proposed examples of structure-based abstractions used to reduce cognitive complexity and illustrated this model as a tool to understand the relationship between these structure-based abstractions and varying airspace structure (Histon, 2008).

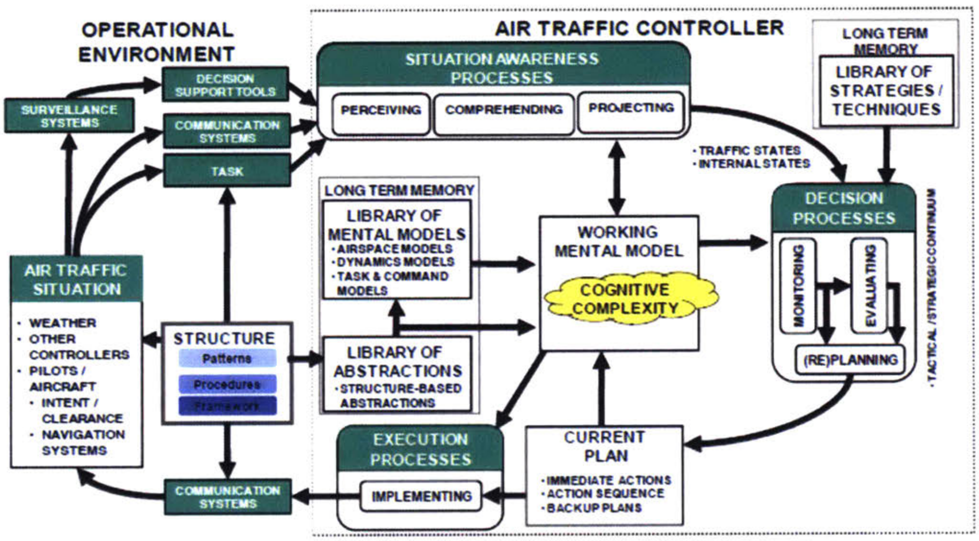


Figure 3-3. Histon's cognitive process model of an air traffic controller (Histon, 2008).

Histon also incorporated the *current plan* (Seamster, Redding, Cannon, Ryder, & Purcell, 1993), the output of decision processes and "an internal representation of the schedule of events and commands to be implemented as well as the resulting trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner" (Histon, 2008). The air traffic situation represents the pilots, aircraft, other controllers, and surrounding environment. Finally, Histon's model explicitly includes the concept of mental models, described next.

Mental model research began in the control domain. Here, most researchers agree that some construct must exist within humans to allow for understanding and control of a system (Veldhuyzen & Stassen, 1977; Rasmussen, 1979; Rouse & Morris, 1985; Rouse & Morris, 1986; Wilson & Rutherford, 1989; Sterman, 1994; Kallus, Barbarino, & Van Damme, 1997). For example, humans have the ability to understand and predict many dynamic situations based on prior system knowledge. Baseball players can predict where a ball will land in the outfield shortly after leaving the bat. The knowledge players have built over time through training and experience is referred to as a *mental model* in much human factors literature (Rasmussen, 1983; Rouse & Morris, 1986; Wilson & Rutherford, 1989; Sterman, 1994; Doyle & Ford, 1998; Veldhuyzen & Stassen, 1977; Moray N. , 1996). However, mental models can be used to explain more than dynamics. One of the most often cited definitions of mental models state, "Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states" (Rouse & Morris, 1986). Mental models can describe why a system exists and what a system looks like. In addition, mental models can help explain how a system operates, and importantly for this research, what a system is currently doing (i.e. the current system state). Wickens argues that mental models are the source of expectancies about how a system will respond (Wickens, Hollands, Banbury, & Parasuraman, 2013), or importantly for this research, predicting the future system state.

Mogford attempted to clarify the distinction between mental models and SA by defining a mental model as a "hypothetical construct that refers to an operator's learning and concepts about a system" (Mogford, 1997). As an organized set of knowledge that has depth and stability over time, mental models are a prerequisite for achieving SA. These are in essence analogs of the external world. Other researchers blur the distinction between mental models and SA, especially in the ATC domain, by using the term *mental picture* as a synonym of a mental model (Kallus, Barbarino, & Van Damme, 1997). They describe mental pictures of a situation as moment-to-moment snapshots of the actual situation based on the mental model and perceived external cues. To avoid ambiguity, this research decouples mental model, an input to the processes that determine state awareness, from *situation awareness*, described next.

3.2 Situation Awareness

Situation awareness has been shown to be a critical aspect of controller cognition. SA has been presented as a predominant and initial component using a descriptive view of human cognition and decision making (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Histon, 2008), the maintenance of which is the controller's primary task (Seamster, Redding, Cannon, Ryder, & Purcell, 1993). Divergence is a measure of state awareness, a subset of SA (Silva, 2016). Understanding the internal mechanisms affecting SA should provide insight to divergence causes.

Situation awareness refers to the up-to-the-minute cognizance required to operate or maintain a system (Adams, Tenney, & Pew, 1995). However, defining SA has proven more challenging and has garnered much research in the aviation domain (Sarter & Woods, 1991; Sarter & Woods, 1995; Endsley M. R., 1995). Sarter and Woods define SA as "a variety of cognitive processing activities that are critical to dynamic, event-driven, and multitask fields of practice" (Sarter & Woods, 1995), suggesting a process-driven concept. Endsley argues SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley M. R., 1988), suggesting a product-driven concept. Endsley further differentiates her product versus process argument by distinguishing the term *situation awareness*, or the state of knowledge, from the process used to achieve it, *situation assessment*. Endsley developed a cognitive model for understanding SA and its role in the decision process, Figure 3-4 (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). Three hierarchical components (or levels) of SA exist. These include Level 1 SA: perception of elements in the environment; Level 2 SA: comprehension of the current situation; and Level 3 SA: projection of future status. Each level of SA builds upon the understanding gained in the previous and signifies a higher level of SA achieved.

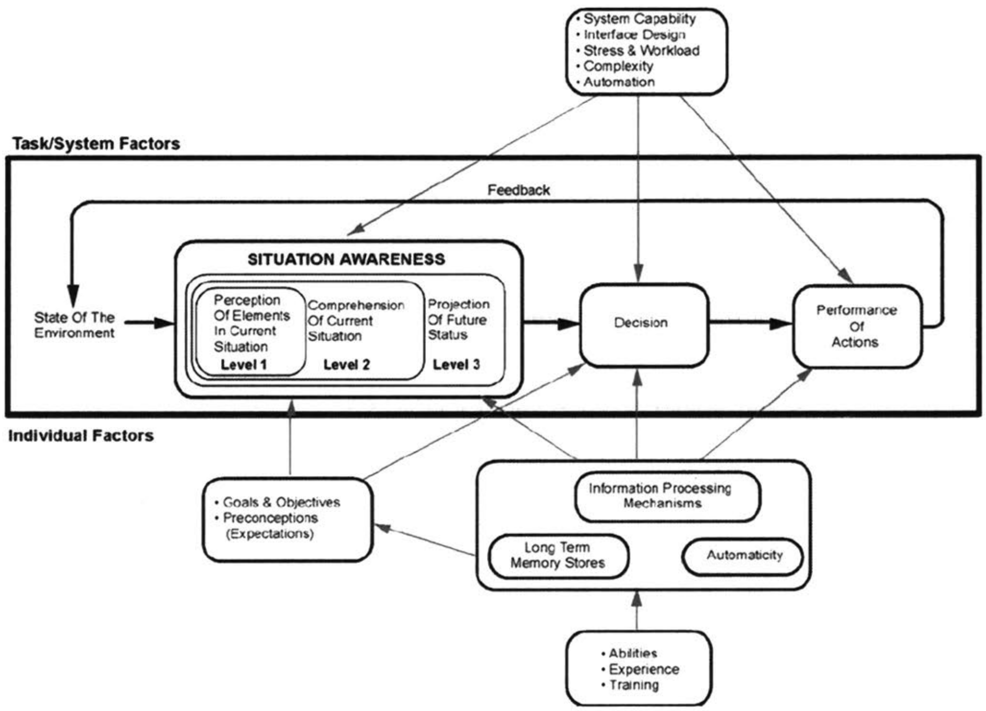


Figure 3-4. Endsley's model of situation awareness in dynamic decision making (Endsley M. R., 1995).

Additionally, the elements that constitute the product of SA have been contentious. Adams, Tenney, and Pew argue SA "means that the pilot has an integrated understanding of factors that will contribute to the safe flying of the aircraft.... The broader this knowledge is, the greater the degree of situation awareness" (Adams, Tenney, & Pew, 1995). This camp believes SA is a combination of the elements constructing the current and future dynamic situation and various static knowledge structures built through training and experience of a specific system or situation. However, researchers such as Rousseau, Breton, and Trembley would support the theory that SA be "defined as a schema depicting the current state of the mental model of the system" (Rousseau, Breton, & Tremblay, 2004).

This research assumes *state awareness*, or the controller's task relevant state vector described in 1.1 Divergence, is a subset of SA. State awareness is a product of state assessment, analogous to situation assessment in Endsley's work, and does not include the process to achieve state awareness, the mechanisms included in the process, or broad static knowledge. This allows for the comparison of the controller's state awareness against the actual system state to determine divergence. However, the process used in determining the state, *state assessment process*, are of critical importance to understand how divergence occurs. In addition, the states measured for divergence are the dynamic states of the system only, specifically the current and future dynamic states, rather than inclusion of static knowledge structures. Based on both Endsley's model of SA and the air traffic controller cognitive process framework, the processes producing state awareness interact with long-term memory stores. This allows further differentiation determining divergence causes, whether due to a state assessment process failure or a static knowledge error input to the process, both important for understanding.

3.3 Human Error

Humans are vulnerable to errors, especially as systems increase in complexity. In that vein, human error has often been recognized as a major source of aviation accidents and incidents (Pape & Wiegmann, 2001; Wiegmann D. A., 2001; Shappell, Detwiler, Boquet, & Wiegmann, 2006; Shappell, et al., 2007; Federal Aviation Administration, 2011). Human error research has attempted to understand how to design systems that overcome these limitations. Reason defined *error* "as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" (Reason, 1990). Divergence can be considered a subset of human error (Silva, 2016), occurring due to a variety of failures, errors, or faults. It is important to differentiate not only the failures, errors, or faults that can lead to divergence to reduce or eliminate its occurrence, but also to differentiate divergence itself to understand if and how divergence leads to a hazardous consequence in a system.

There are many views regarding the causes of error within a human operator, controller, or supervisor. One view describes errors in relation to an operator's intended or unintended behavior, whether it be action or inaction. An *error of omission* occurs when a required action is not performed by an operator; while an *error of commission* occurs when an inappropriate action is performed (Proctor & Van Zandt, 2008). Further decomposition of errors of commission lends timing errors, sequence errors, selection errors, and quantitative errors (Proctor & Van Zandt, 2008). A *timing error* occurs when a human performs an action at the incorrect time, too early or too late. A *sequence error* occurs when a human performs a series of actions in the wrong order. A *selection error* occurs when a human activates, manipulates, or otherwise handles the wrong control or effector. Finally, a *quantitative error* occurs when the magnitude of the control action is too great or too slight. Another view of human error considers various stages of human cognition processing and categorizes errors based on their origin. Reason outlined a taxonomy by defining *error types* relating to the origin of an error within the stages involved in conceiving and carrying out an action sequence (Reason, 1990). Under Reason's model, the three cognitive stages of planning, storage, and execution correspond to the primary error types of mistakes, lapses, and slips shown in Table 3-1 (Reason, 1990).

Table 3-1. Classifying the primary error types, adapted from (Reason, 1990).

Cognitive Stage	Primary Error Type
Planning	Mistakes
Storage	Lapses
Execution	Slips

A *slip* is a form of human error defined to be the performance of an action not intended (Norman, 1981). Slips can occur for a variety of reasons, attentional failures being common. On the other hand, a *lapse* involves memory failures of an otherwise correct intention (Proctor & Van Zandt, 2008). Finally, a *mistake* is characterized by an incorrect intention or an error in planning due to failures in judgment or inference. In addition to diagnosing human error based on the location of the error, Reason defined *error forms* as recurrent varieties of fallibility that appear in all cognitive activity (Reason, 1990). He argued that error forms are primarily shaped by two factors: similarity and frequency. *Similarity-matching* is concerned with assigning items from memory based on cues delivered through the human senses (Reason, 1990). Whereas *frequency-gambling* describes the selection from among candidates in memory biased in favor of the more frequently-encountered items (Reason, 1990). Errors can occur in these forms within any cognition stage.

Reason related his work to Rasmussen's framework of skill-, rule-, and knowledge-based levels of behavior because he felt describing human error with slips and mistakes inadequately differentiated error. Rasmussen illustrated three levels of performance of skilled human operators shown in Figure 3-5 (Rasmussen, 1983). Skill-based behavior represents sensory-motor performance during acts or activities which take place without conscious control as smooth, automated, and highly integrated patterns of behavior (Rasmussen, 1983). Rule-based behavior is composed of a sequence of subroutines in a familiar work situation typically controlled by a stored rule or procedure (Rasmussen, 1983). Knowledge-based behavior typically occurs during unfamiliar situations for which no know-how rules for control are available and the goal must be explicitly formulated based on an analysis of the environment and the overall aims of the person (Rasmussen, 1983).

Rasmussen described errors and behavioral levels through a HIP framework. Specifically, skill-based errors typically are related to variability of force, space, or time coordination (Rasmussem, 1982). Rule-based errors are typically related to mechanisms such as incorrect classification or recognition of situations, incorrect associations, or memory lapses (Rasmussem, 1982). Finally, knowledge-based errors are much harder to define, and can only be defined within the context of the goal attempted by the human (Rasmussem, 1982).

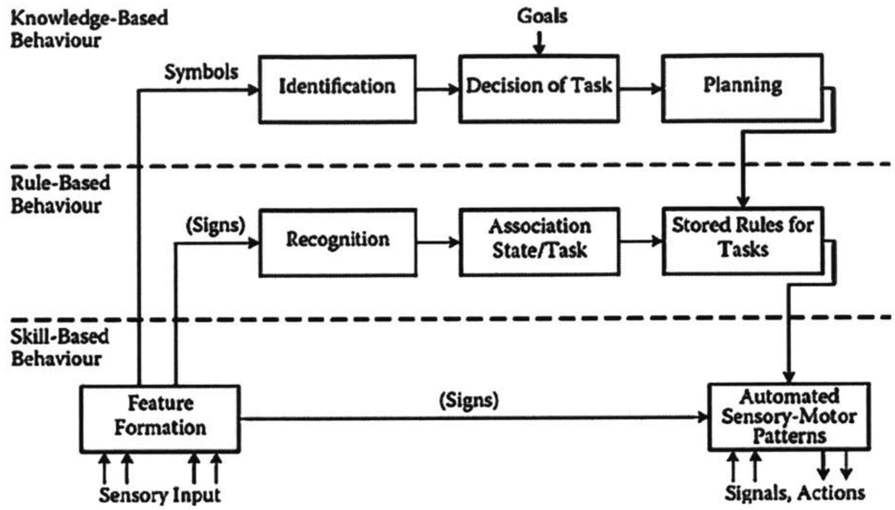


Figure 3-5. Levels of performance of skilled human operators (Rasmussen, 1983).

Using Rasmussen's framework, Reason described unsafe acts committed by humans that affect systems. From Figure 3-6, *violations* are deliberate, but not necessarily reprehensible deviations from practices deemed necessary to maintain the safe operation of a potentially hazardous system (Reason, 1990). These can be distinguished between *routine violations*, habitually forming behavior, and *exceptional violations*, singularly occurring in a particular set of circumstances (Reason, 1990). It is important to distinguish that some violations may be unintentional while others deliberately malicious or acts of sabotage.

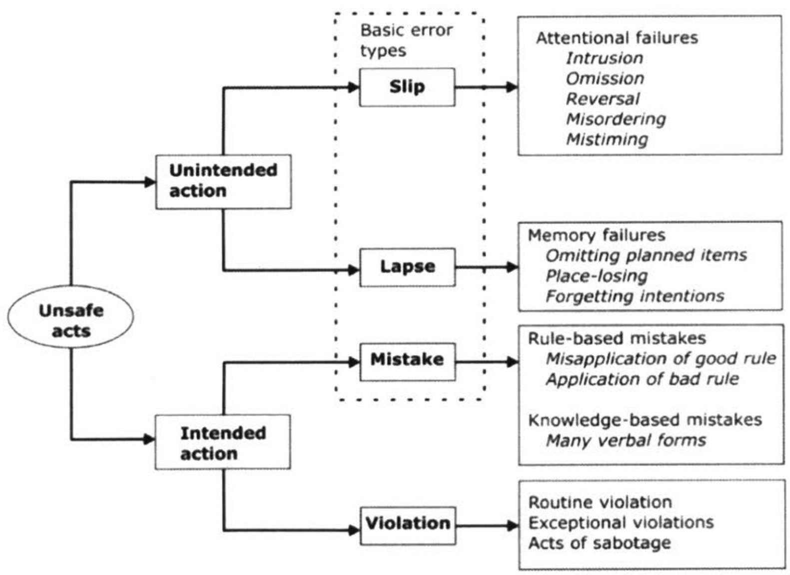


Figure 3-6. A classification of unsafe acts (Reason, 1990).

With Rasmussen, Reason, and others as a basis for classification, Endsley conducted research on failures of human decision making frequently cited in aviation investigations and determined five separate categories of causal factor for human error (Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995). She determined the most prevalent factor for human error in aviation was SA. Other factors included *physiological* degradation, such as fatigue or drug use, and *procedural* errors in which a violation of an existing procedure occurred, such as omitting a task or executing a task incorrectly. Also, *psychomotor* reasons where the primary cause of the human error was within the execution of the action itself, such as aircraft control, was another factor. The final factor was *decision making*, where the human had accurate information on the situation but errored nonetheless contributed. These various causal factors align with the previous view of categorizing errors within separate human cognitive processes, such as situation assessment, decision making, execution, memory, and human factors.

According to Jones, errors in SA can be categorized through the lens of Endsley's three levels (Jones & Endsley, 1996; Jones D. G., 1997). Here, Jones described Level 1: failure to correctly perceive the situation; Level 2: improper situation integration or comprehension; and Level 3: incorrect projection of future system actions. Within the context of divergence, SA-like errors could lead to current or future state divergence. Again, although divergence encompasses the current and future dynamic system states only, a human's understanding of non-dynamic system aspects may be in error and contribute to divergence. For instance, incorrect knowledge in long-term memory could lead to a divergence when this incorrect knowledge affects a dynamic system state. As part of her own model of SA, Endsley decomposed SA errors into either *incomplete SA*, knowledge of only some of the elements, or *inaccurate SA*, erroneous knowledge concerning the value of some elements (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). These errors not only occur within each of the three levels of SA, but can be caused by various failures or due to various mechanisms. Jones and Endsley identified various error forms in Table 3-2 below (Jones & Endsley, 1996; Jones D. G., 1997).

Table 3-2. Taxonomy of levels of situation awareness errors, adapted from (Jones D. G., 1997).

Level 1: Failure to correctly perceive the situation
• Data not available
• Hard to discriminate or detect data
• Failure to monitor or observe data
• Misperception of data
• Memory loss
Level 2: Improper integration or comprehension of the situation
• Lack of or poor mental model
• Use of incorrect mental model
• Over-reliance on default values
• Other
Level 3: Incorrect projection of future actions of the system
• Lack of or poor mental model
• Over-projection of current trends
• Other

As part of the situation assessment process, projecting future states predispose humans in their perception and are especially critical in time-constrained environments. Expectations allow humans to process information faster when the stimulus is consistent; however, when the stimulus is inconsistent with the expectation, errors are more likely (Jones R. A., 1977). Generically, *expectation bias* refers to humans seeing or hearing what they expect to see or hear (Shorrock & Kirwan, 2002). Specifically, *expectation bias* refers to the manipulation of perceived elements to values consistent with the human's expectation (Bhattacherjee, 2001; Silva, 2016).[8] Expectation bias can develop in the perception process when expectations are so strong they lead to a misperception of an observable or lead to poor information sampling or attention allocation. Additionally, expectation bias can develop in the comprehension process due to association and inference errors based on incorrect state probabilities of ambiguous observations.

Silva described a common cause of "pilot error" as divergence between the crew's interpretation of the system state from the actual system state (Silva & Hansman, 2015). This research highlighted mode awareness or mode confusion,[9] leading to automation surprise,[10] as a manifestation of divergence stemming from an error in the controller's mental model. Shown in Figure 3-7, system state understanding is temporal and the causes can vary.

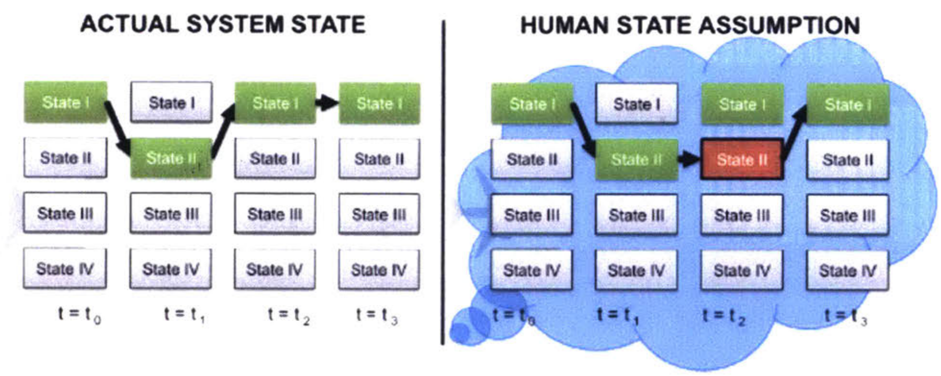


Figure 3-7. Human state assumption and divergence profile through time (Silva, 2016).

Silva developed a HIP model of divergence to determine diverged or converged human states, building upon the work of Wickens (Wickens, Hollands, Banbury, & Parasuraman, 2013) and Endsley (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). This work characterized divergence as process failures from the human observation process, association process, selection process,

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[8] In current literature, *expectation bias* is considered a subset of the more traditional psychology term *confirmation bias*. *Confirmation bias* is defined as the seeking or interpreting of evidence in ways that are partial to existing beliefs, expectations, or a hypothesis in hand (Nickerson, 1998). Researchers have argued the term *confirmation bias* describes the spectrum of intentional and unintentional seeking of confirming evidence. However, this research is interested in the unintentional act leading to error, which is described later in perception and comprehension processes as *expectation-driven bias*.

[9] Also referred to as *mode errors*, it occurs when the human operator loses mode awareness, defined as the "awareness of the status and behavior of the automation" (Mouloua, Hancock, Jones, & Vincenzi, 2010).

[10] Automation surprise occurs when automated systems behave in ways the operators do not expect (Mauro, 2017).

and expectation process utilizing the model shown in Figure 3-8, but was limited in scope to current state awareness rather than a human's predictions of future states.

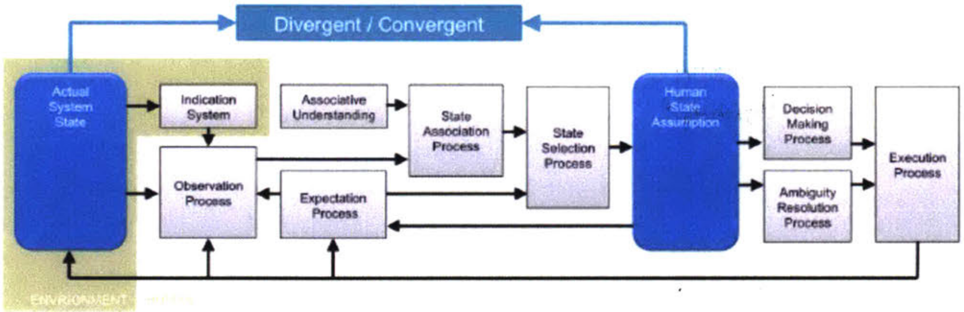

Figure 3-8. Human information processing model of divergence (Silva, 2016).

To better analyze and specify the causes of controller divergence, this research incorporated Silva's concept of the human state assumption compared with the actual system state within a more robust controller processing model. In addition, this research relates the causes of divergence similarly to a SA error as shown in Table 3-2, but more specifically. Here, divergence is proposed to result from a more comprehensive variety of process failures, knowledge errors, or erroneous system inputs. In addition, divergence may solely or in concert with other human error described in Figure 3-6 lead to hazardous consequences in a system.

3.4 Risk Analysis and Accident Causation

After using cognitive process models to understand divergence causes, risk analysis and accident causation theories were reviewed to understand human error consequences. Theories for risk analysis and accident causation have evolved, growing from sequential models to system-level or multi-causality models. As systems grow more complex it is reasonable to assume the factors contributing to risk will grow as well. While the focus of this research is divergence, literature was reviewed to understand possible divergence consequences and how divergence interacts with other events to result in an accident.

One of the first accident causation models was developed by Heinrich, known as "domino theory," which regards accidents as a sequential series of factors resulting in injury, shown in Figure 3-9 (Heinrich, Petersen, & Roos, 1980).

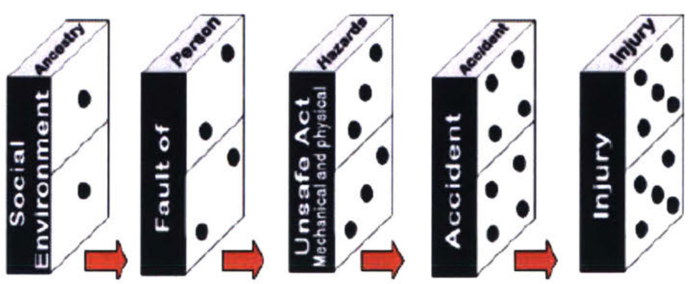

Figure 3-9. The five factors in the accident sequence (Klockner & Toft, 2015).

According to domino theory, the injury results from an accident caused by an unsafe act or mechanical or physical hazard. These unsafe acts or hazards are the result of the fault of a person through recklessness or ignorance, among other reasons. Many unsafe acts could be characterized by human error described earlier. Next, the reason for a person's fault is either ancestry or the social environment. Although Byrd proposed updates to the domino theory model in 1976 (Katsakiori, Sakellaropoulos, & Manatakis, 2009), Reason was concerned that accident investigations were too focused on active operator errors and equipment failures, and introduced two kinds of errors along with the concept of multi-causality.

Reason began by codifying the distinction between *active errors*, errors associated with the performance of front-line operators, and *latent errors*, errors associated with the performance of humans removed in both time and space from control (Reason, 1990). While active errors have been described earlier as slips, lapses, and mistakes, this research emphasized latent errors posed the greatest threat to the safety of complex systems, yet most accident analysis at the time focused on active operator errors or equipment failures. Finally, Reason argued that most accidents are caused "by the unique conjunction of several necessary but singly insufficient factors" (Reason, 1990). While his model, what came to be known as the "Swiss cheese" model, appears linear as seen in Figure 3-10 and Figure 3-11, the underlying theme implies an accident could result from multiple interacting active and latent errors.

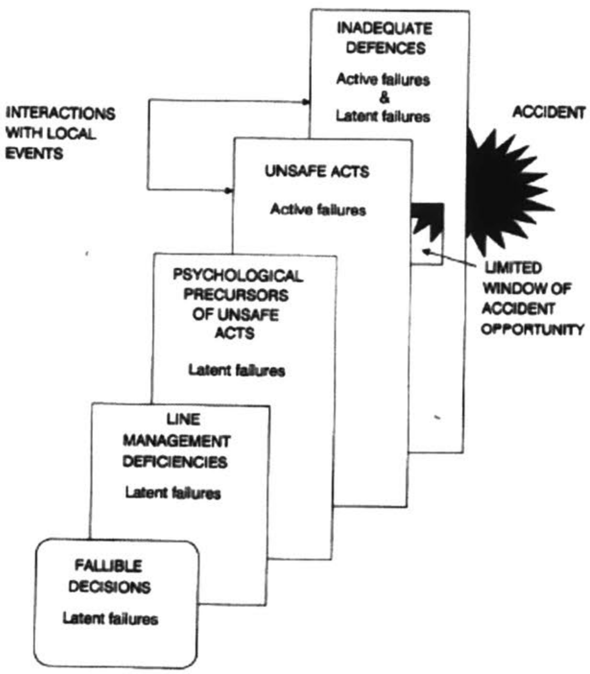

Figure 3-10. Human contributions to accidents (Reason, 1990).

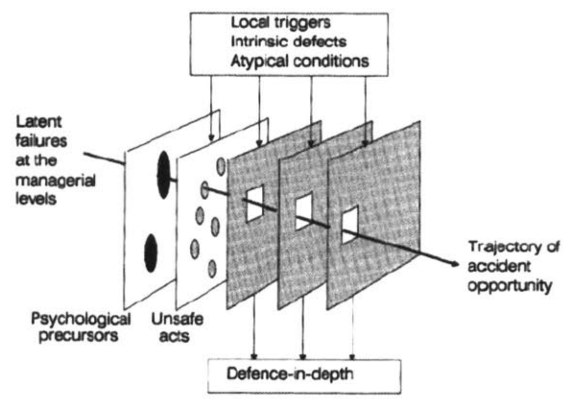

Figure 3-11. The dynamics of accident causation (Reason, 1990).

Building on the context of multi-causality accidents, Rasmussen introduced an accident causation model with multiple layers of a sociotechnical system. Rasmussen aspired to capture levels of risk ranging from legislators to managers and planners to operators (Rasmussen, 1997), similar to Reason's management deficiencies but to a greater degree. He was concerned that various system levels are analyzed by their respective academic disciplines rather than by cross-disciplined studies considering risk management as a control problem. Finally, Rasmussen argued risk management required a system-oriented approach based on functional abstraction rather than structural decomposition (Rasmussen, 1997).

Leveson extended Rasmussen's work by introducing an accident analysis concept named STAMP (Systems-Theoretic Accident Model and Processes) based on systems theory which emphasizes enforcing behavioral safety constraints over preventing failures (Leveson N. G., 2011). STAMP uses the concepts of safety constraints, hierarchical safety control structures, process models, and basic systems theory to illustrate all factors involved in an accident, including those related to social and organizational structures. The basic control loop upon which a system is described is in Figure 3-12 with a more complex hierarchical model similar to Rasmussen. Component interaction accidents and indirect or systemic causal mechanisms are emphasized in her definition of accident causation (Leveson N. G., 2011).

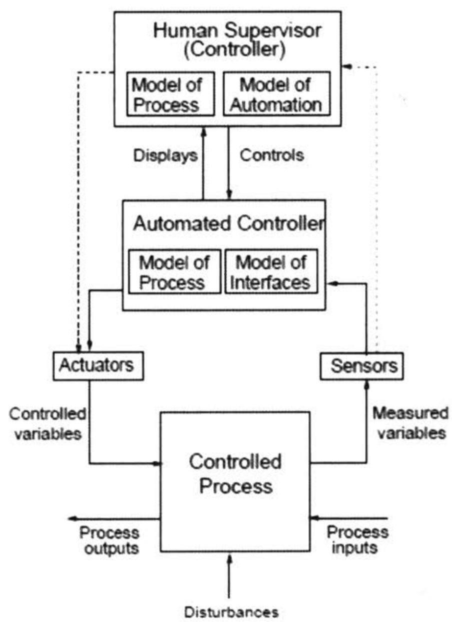

Figure 3-12. Typical control loop and the process models involved in a system (Leveson N. , 2004).

Research by Reason, Leveson, and others provide not only additional information regarding human controller error, but also the concept of latent errors to describe errors outside the human controller which may affect the system, valuable since a major focus of this research is to understand divergence consequentiality. To further investigate the consequences of divergence and how divergence interacts with agents, objects, environments, procedures, and other errors in a system, numerous methods for risk analysis and accident investigation were reviewed. Some accident models classified as HIP accident models, such as HFACS (Human Factors Analysis and Classification System), WAIT (Work Accidents

Investigation Technique), and SCAT (Systematic Cause Analysis Technique), are useful in light of the focus on human error and categorizing causes of divergence in this research. HFACS identifies and organizes latent error using a hierarchical structure involving organizational influences, unsafe supervisory actions, preconditions for unsafe acts, and unsafe acts (Scarborough, Bailey, & Pounds, 2005). It has been used to examine ATC operational errors (Scarborough, Bailey, & Pounds, 2005), ATC related accidents and incidents (Pape & Wiegmann, 2001), and US Air Force (USAF) aviation mishaps (Gibb & Olson, 2008). WAIT attempts to identify active failures, influencing factors and latent conditions, and classify and code them in primarily occupational accidents and incidents in industrial activity (Jacinto & Aspinwall, 2003). Again, integrating theory by Reason, the method uses questionnaires and diagram flows to provide deficiencies in the workplace (Jacinto & Aspinwall, 2003; Katsakiori, Sakellaropoulos, & Manatakis, 2009). SCAT integrates domino theory into a charted framework using checklists designed to investigate occupational accidents within industry (Kjellen & Hovden, 1993). Understanding methods of diagram flows, investigative questions, and coding informed methods used in this research to understand divergence causes and factors relating to consequences.

Developed by Bell Laboratories, Fault Tree Analysis (FTA) is a top-down, systematic deductive process using Boolean logic to identify immediate and basic causes of an event (Katsakiori, Sakellaropoulos, & Manatakis, 2009). The fault tree explicitly shows the relationships necessary to result in the top event and provides a framework for evaluation of the top event (NASA Office of Safety and Mission Assurance, 2002). Figure 3-13 depicts a simplified fault tree where the top event, 'D Fails,' occurs when the gate 'G1' is passed through by the combination of 'A Fails' and 'B or C Fail,' with the probability of each failure annotated in the small circles below each lower event.

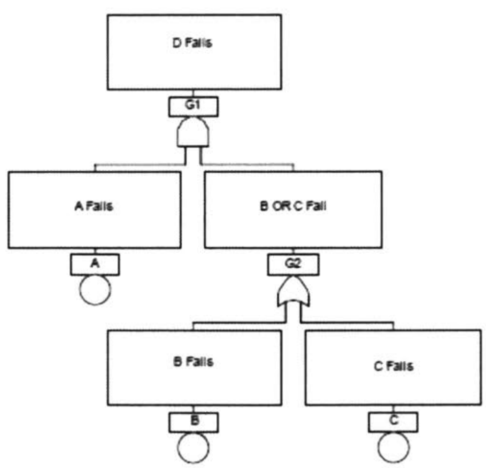

Figure 3-13. A simplified fault tree (NASA Office of Safety and Mission Assurance, 2002).

Similarly, an Event Tree Analysis (ETA) is a bottom-up, systematic inductive process used to analyze sequences following after an event (Sklet, 2004). The sequence following an initiating event is influenced by Boolean logic successes or failures of barriers or safety systems that lead to a set of consequences. Figure 3-14 illustrates a simplified event tree, showing the initiating event, subsequent events, the consequences, and the probability of their occurrence.

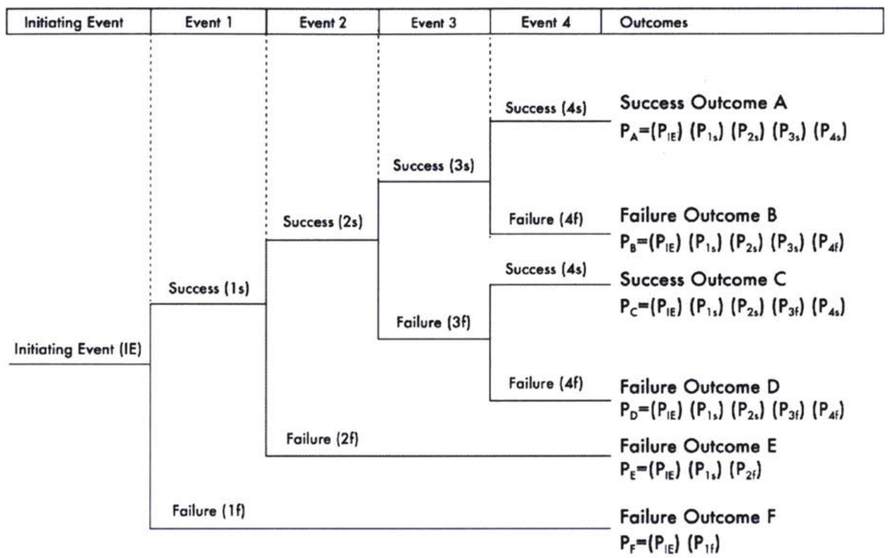

Figure 3-14. A simplified event tree (Resilinc, 2016).

The bowtie method has been used successfully to identify hazards, develop systems and procedures to eliminate or reduce hazards, and mitigate consequences after a hazard has occurred (Alizadeh & Moshashaei, 2015). The bowtie method is simply a fault tree on the left-hand side, an event tree on the right-hand side, and the hazard or hazardous event illustrated as the 'knot' at the center of the diagram, shown in Figure 3-15. After determining the events leading to and following the hazardous event, qualitative or quantitative analysis can create safeguards to control unwanted events and consequences.

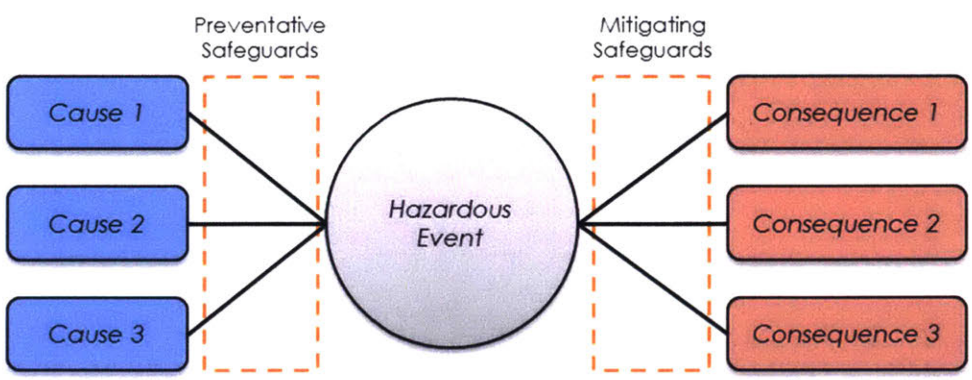

Figure 3-15. Bowtie method diagram, adapted from (Fisher, Ebrahim, & Sun, 2013).

The bowtie method begins with the hazard or hazardous event. In application to aviation, the FAA defines a *hazard* as "a condition that could foreseeably cause or contribute to an accident" (Federal Aviation Administration, 2012); while an *accident* is an occurrence of harm to people or damage to property or the environment in the operation of a system. In addition, the *hazardous event* is generally defined as the moment when a level of control over the hazard is lost and shown as the 'knot' in the middle of the diagram. Essentially, the hazardous event will lead to a consequence unless mitigated prior.

To the left of the hazardous event is a FTA, where causes, or threats, to the hazardous event are shown. Examples of causes of the hazardous event include human error and system malfunctions or equipment failure. To the right of the hazardous event is an ETA, where *consequences* are shown that can occur from the event. Between both the causes and hazardous event and the hazardous event and consequences, barriers are put in place to prevent the manifestation of the hazardous event or later consequence from occurring. These barriers may be successful or unsuccessful in mitigating the hazardous event or consequence. The bowtie method was selected as a method for this research and will be described further in 4.1 Development of the Cause and Consequence Framework.

3.5 Summary

Experimental data in the domains of psychology and cognitive science have coalesced on consistent concepts for descriptive HIP models, with many based on the work of Wickens, especially in the aviation domain. In the subject of controllers, Histon's cognitive process model was based on the seminal work of Endsley (situation assessment processes) and Pawlak (decision making processes), and was used as the basis for the air traffic controller cognitive process framework. Although the concept of SA has been challenging to define and researchers have argued whether to treat SA as a product or process, dynamic or static, this research investigated the dynamic product of state following Silva's state-based description of divergence as a subset of SA. Using this focus, divergence was investigated using a similar taxonomy as the one of SA error developed from the work of Jones and Endsley. However, many of the underlying causes of divergence are still related to the broader area of human error research, which is fairly consistent. Finally, although many risk and accident analysis methods have been proposed, much of the research has been developed from Reason's theories of active and latent errors, along with the layers associated with his model. With a healthy understanding of the latent errors possible within a system, this research utilized a bowtie method to illustrate causes and consequences along with proposed design mitigations for past and future systems.

4 Air Traffic Controller Divergence Cause and Consequence Framework

To understand how to minimize divergence and its consequences in human controllers while they manage a human-integrated system, an air traffic controller divergence cause and consequence framework was developed. The cause and consequence framework allows visualization of the relationship between an undesirable event, its causes, its consequences, mitigations to reduce or eliminate the causes, and mitigations to limit the consequences (Rheinboldt, 2017). Focusing on the causes and consequences of controller divergence, the framework illustrates various pathways from the causes of divergence culminating in a hazardous or non-hazardous consequence, as well as potential mitigations.

To understand and elucidate the causes of divergence and its consequences relating to controller cognition, an air traffic controller cognitive process framework was developed. HIP models, such as the cognitive process framework, provide a useful means for analyzing the different psychological processes interacting with systems and characterizing the flow of information as a human performs tasks (Wickens, Hollands, Banbury, & Parasuraman, 2013). Together these two tools were utilized to understand the causes and consequences of divergence in ATC accident and incident case studies. Then they were utilized as tools to understand controller divergence vulnerabilities within an UAS-integrated NAS.

4.1 Development of the Cause and Consequence Framework

The development of the air traffic controller divergence cause and consequence framework was an iterative process beginning with a literature review described in 3.4 Risk Analysis and Accident Causation. After developing an initial construct, ATC accident and incident case studies were analyzed to refine the diagram for use in the final portion of the thesis, the UAS-integrated NAS analysis.

4.1.1 Framework Developed from Literature

This framework representation was chosen because it focuses on an 'event' at the illustration's center and presents the causes and consequences of that event (Rheinboldt, 2017), as seen in a typical bowtie method diagram in Figure 4-1. The causes of the hazardous event are identified using a FTA on the left-hand side and the consequences of the hazardous event are identified using an ETA on the right-hand side.

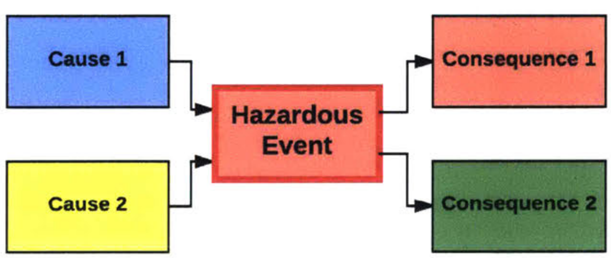

Figure 4-1. Typical bowtie method diagram.

A bowtie method representation also allows for multiple disciplines of analysis, with theory based on Reason's "Swiss cheese model" (Alizadeh & Moshashaei, 2015), such as hardware failures, software failures, human error, procedural issues, and architecture and structural shortcomings. In addition, it provides structure to develop mitigations for both the causes and consequences of an event.

4.1.2 Framework Developed from Case Study Analysis

Divergence is represented as the hazardous event or 'knot' in the framework. Too often human failure is treated generically, but this representation focuses the controller failure specifically to divergence and its ramifications. With divergence as the hazardous event, it becomes the top event in the FTA and initiating event in the ETA, correlating well to the research objectives with divergence causes and consequences visually depicted.

Divergence, an inconsistency between controller state awareness and the actual system state, is visually represented on the left-hand side of Figure 4-2. As discussed in Chapter 1, divergence can be consequential or inconsequential, and is represented as branches on the right-hand side of Figure 4-2.

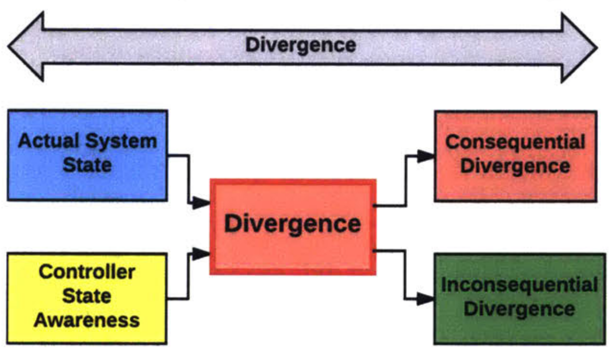

Figure 4-2. Divergence causes and consequences represented using a bowtie method diagram.

Figure 4-2 will form the center of the framework, which will be expanded with the causes and consequences of divergence. Before the expansion, more details regarding the state compared between the system and controller within this framework are warranted.

4.1.3 State

To compare the actual system state and controller state awareness, an understanding of state is required. The *state* is defined as a set of variables and their associated values used to describe a dynamic system as a function of time. State could be considered a vector, $x_i(t),\ i = 1, \dots, n,$ with n variables as a function of time. This formalized framework of a state vector model was used by Reynolds and Hansman to describe current and future aircraft behavior to investigate conformance monitoring (Reynolds & Hansman, 2000; Reynolds & Hansman, 2001; Reynolds & Hansman, 2003). This research compares the actual system state to controller state awareness, shown in Figure 4-2.

4.1.4 Actual System State

The actual system state are the state variables and their values as a function of time directly corresponding to state variables for the controller's task relevant state, discussed in 4.1.5 Controller State Awareness. In essence, the actual system state is the truth value of the system. In order to effectively manage the system, the human must acquire, understand, remember, and often project system state to make appropriate decisions for future control actions. The actual system state is determined by the air traffic situation.

4.1.4.1 Air Traffic Situation

The air traffic situation within the air traffic controller cognitive process framework, represents the agents, objects, interfaces, structure, and environment that combine to form both the system the controller manages and the means to accomplish their tasks. Aircraft are the primary objects managed by controllers. To accomplish their task, aircraft must be properly identified through beacon and radar surveillance, flight plans, and controller-pilot communications. This identification, represented through a registration number or aircraft call-sign (Federal Aviation Administration, 2015), is used for data or voice communications between the controller and pilot. Pilots are the primary agents managed by controllers as the pilots directly operate the aircraft. To actively manage the pilot agents controllers use interfaces, primarily standard voice or data communications as previously described. The controller's station is the primary means of observing the air traffic situation. The primary displays consist of the TSD and FPS described in 2.2.4 Air Traffic Control Stations and Structure, along with previously mentioned communication and automation tools. In addition, fellow controllers interact with the air traffic situation when providing handoffs, pointouts, and other communication to the primary controller as described in 2.2.2 Air Traffic Controller Division of Labor. The NAS airspace is structured as described in 2.1 National Airspace System and common understanding is assumed for pilots and controllers. This lends itself to SOPs used to maintain safety and efficiency between pilots and controllers and between the aircraft themselves. Finally, the environment can impact the air traffic situation due to weather phenomenon, day versus night, and other events affecting operations. If the controller state awareness, discussed next, is inconsistent from the actual system state they are diverged.

4.1.5 Controller State Awareness

State could be an infinitely large vector. However, as discussed in 1.1 Divergence, the controller is not necessarily concerned with the entire system state, but only the task relevant state, defined as a subset of the total state vector relevant for the human's particular task. Although the variables within the controller's task relevant state may change from moment to moment and depend on the type of control, some common themes should be understood.

First, the controller needs to understand multiple variables regarding aircraft they are controlling, such as the aircraft's position, velocity, and identity. Second, the controller may need to understand some variables regarding the pilot controlling the aircraft, such as their intent, usually understood as their clearance. Third, the controller may need to understand relational states between the aircraft and other objects, such as aircraft, obstacles, terrain, and weather to accomplish their task. Fourth, a controller does not act alone within a control facility and may consider other controller communication and coordination, such as when another controller coordinates a commanded altitude. Fifth, the controller may need to understand other system information to effectively control aircraft within it, such as information regarding the current system structure like the runway in use or Minimum Vectoring Altitude (MVA) at a particular location. Sixth, controllers manage aircraft within an environment, and will need to understand the environmental state such as winds and inclement weather.

To accomplish their task the controller needs to understand the system state at the current moment in time and also some time in the near future. Therefore, this thesis separates controller state awareness into the controller's *current state assumption* and *future state projection*. First, the human must understand the current system state, which is often realized by controllers through a combination of sensors and displays, along with direct aircrew communication and often in tower facilities, direct observation. The *current state assumption* can be defined as the human's mental representation of the system state relevant for the human's task at the current moment in time. Current states are managed in working memory, updated through the state assessment process, yet can fade over time. The current state assumption can be described by the vector $X(t_C)$, or the vector at the *current time*. Second, some system states must be projected into the future to accomplish the human's task, which in the case of a controller is to maintain safety. These states are realized through a combination of displays, automation tools, communication, and mental simulation. The *future state projection* can be defined as the human's mental representation of the system state relevant for the human's task as a function of time. The future state projection is projected forward the length of time required for the human's planning toward the task. Projected states are managed in working memory, updated through the state assessment process, but can fade over time. The future state projection is described by the vector $X(t_F)$, or the vector at a *future time*. Future states may consist of contingencies (i.e. branches), or multiple possible states each with associated probabilities bases on various contingencies that could occur in the future. Also, current and future states may include a level of uncertainty.

While many of the variables in the current state (within some minimum and likely inconsequential time delay) can be either perceived by the controller or measured by an outside viewer, the future system state may be unknown. However, the future state is extremely important for a controller based on their task to maintain separation. Unfortunately it is impossible to know whether the controller's future state projection is accurate or not until the future occurs. Therefore, the measurement of the consistency of controller state awareness compared with the actual system state can only occur post-event. Regardless, this representation allows for investigation and analysis of state changes and comparisons between the controller state awareness and actual system state.

To understand how the controller may diverge in their understanding of the system state, in other words to understand the causes of divergence, an aid to understand how the controller forms their state awareness was needed. Therefore, an air traffic controller cognitive process framework was developed.

4.2 Development of the Air Traffic Controller Cognitive Process Framework

To understand controller state awareness as part of the air traffic controller divergence cause and consequence framework, an air traffic controller cognitive process framework was developed. This development process was iterative, beginning with a literature review of HIP, SA, and human error described in Chapter 3. After developing an initial framework, ATC accident and incident case studies were analyzed to refine the framework for use in the final portion of this thesis, the UAS-integrated NAS analysis. This section describes major developmental changes to the framework while the final version of the framework is described in 4.3 Air Traffic Controller Cognitive Process Framework.

4.2.1 Framework Developed from Literature

The air traffic controller cognitive process framework was based on Histon's cognitive process model for air traffic controllers (Histon, 2008), relating the air traffic situation to controller cognition. To determine divergence, the model was expanded using Silva's notion of a convergence/divergence comparator between the actual system state and controller state awareness (Silva, 2016). The SA process of Histon's model was expanded using SA literature primarily from Endsley (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995), but was transformed from SA to state assessment in accordance with the context of divergence.

4.2.2 Framework Refined through Case Study Analysis

The air traffic controller cognitive process framework was refined through ATC case study analysis, which will be described in Chapters 7 and 8. From case study analysis, future state projection was added to the state assessment process that compared the controller's future state projection with actual system future states, which was not previously incorporated in Silva's framework. Also, working memory was explicitly added to the framework to illustrate memory failures as a cause of divergence following an otherwise consistent state assessment. In addition, an abstraction of the concept of a mental model was added in each major cognitive process with knowledge input from long-term memory. Expectations were found to be a major influence on state assessment, and these inputs were decomposed into specific portions of the framework. Finally, known diverged states were determined to be a subset of controller state awareness and were explicitly represented in both a divergence assessment process and within the current state assumption. Although this model is built specifically for controllers, it is hypothesized to be generalizable to any system characterized by a human managing dynamic agents through state observation and actions. These additional applicable systems are discussed in 11 Conclusions.

4.3 Air Traffic Controller Cognitive Process Framework

The air traffic controller cognitive process framework is shown in Figure 4-3. The framework consists of three major areas, the state convergence/divergence comparator, the air traffic situation, and the air traffic controller. The state convergence/divergence comparator represents an outside vantage point and compares the actual system state to controller state awareness to determine convergence or divergence. This correlates with the divergence block in the cause and consequence framework, Figure 4-2. The air traffic situation, in blue, represents the system outside of the controller, essentially both the outside world and controller interfaces. The air traffic controller section, in green, represents controller cognition.

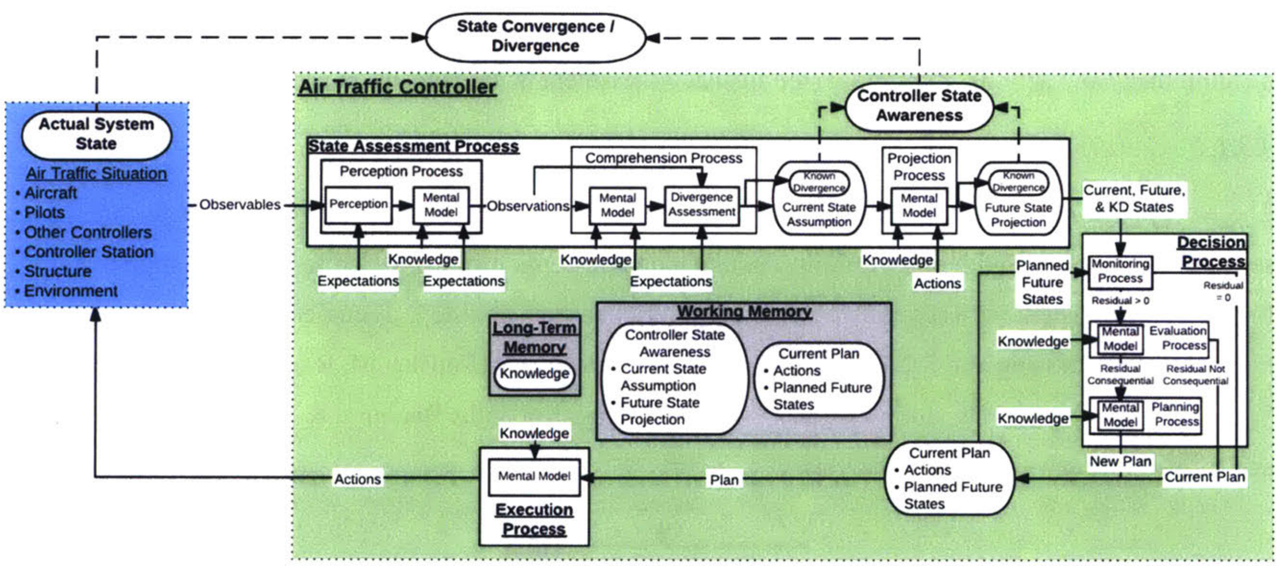

Figure 4-3. The air traffic controller cognitive process framework.

The air traffic controller section of the cognitive process framework, shown in green, consists of three major processes analogous to many of the HIP models described in 3.1 Human Information Processing (Proctor & Van Zandt, 2008; Wickens, Hollands, Banbury, & Parasuraman, 2013). These include the state assessment processes analogous to perception (Proctor & Van Zandt, 2008; Wickens, Hollands, Banbury, & Parasuraman, 2013), decision processes analogous to cognition (Proctor & Van Zandt, 2008) or decision and response selection (Wickens, Hollands, Banbury, & Parasuraman, 2013), and the execution process analogous to action (Proctor & Van Zandt, 2008) or response execution (Wickens, Hollands, Banbury, & Parasuraman, 2013). These processes are further delineated to elucidate their relationship with divergence and are discussed in their own separate section below. However, the state assessment process directly determines controller state awareness, shown in Figure 4-2 as an input to determine divergence. As shown in Figure 4-3, the first main controller cognitive process within the cognitive process framework is state assessment, which directly produces controller state awareness.

4.3.1 State Assessment Process

The *state assessment process* represents the combined processes used to acquire and maintain state awareness and consists of three sub-processes, the perception process, comprehension process, and projection process, which are consistent and analogous to Endsley's three levels of SA and the processes used to obtain them (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). Here, state assessment consists of the same sub-processes and functions of situation assessment in Endsley's model, but produce a more precise output used in this research, a state vector to compare to the actual system state rather than SA in general terms. Regardless, information is received by the controller through air traffic situation observables, transformed within the state assessment process to current and future states, before being passed to the decision and execution processes outside of state assessment to develop plans and actions. The initial step in state assessment is the perception process.

4.3.1.1 Perception Process

The *perception process* within state assessment is represented as the process where observables are sensed and associated with observations. An expanded perception process representation is shown in Figure 4-4, consistent with research conducted by Wickens and Endsley, discussed in 3.1 Human Information Processing and 3.2 Situation Awareness respectively (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Wickens, Hollands, Banbury, & Parasuraman, 2013), and refined through case study analysis.

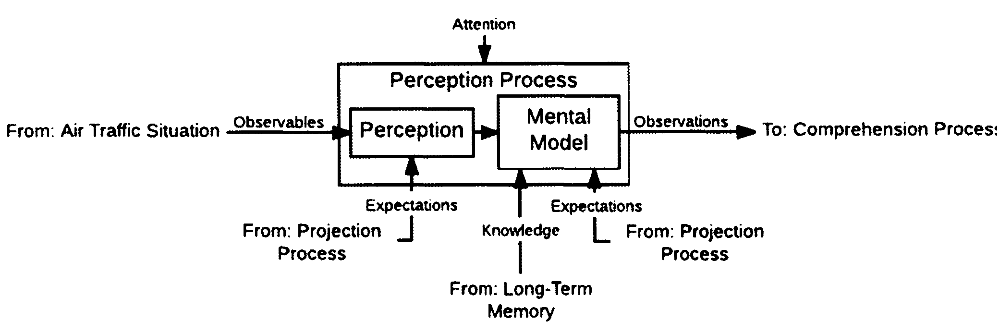

Figure 4-4. Perception process representation.

Observables can be defined as indications that provide useful information to the human regarding the system state (Silva, 2016). Observables originate from the air traffic situation, and as discussed in 2.2.4

Air Traffic Control Stations and Structure, are primarily provided by displays, communication systems, and through direct perception of the air traffic situation, which is common for tower controllers. On the other hand, center and terminal controllers will often use displays as their primary reference to accomplish their task, constantly acquiring observables to update their state awareness. These observables may come in different modalities.

Within the perception process there are two sub-processes represented, perception and the mental model.

4.3.1.1.1 Perception Sub-process of the Perception Process

The first component represented in the perception process is the perception sub-process, which accounts for sensing observables. Although observables may be present in the air traffic situation, perception is required for these observables to be acquired and passed to the mental model in the perception process for transformation to observations. Perception uses multiple senses, primarily the visual and auditory channels for controllers. Perception is influenced by attention, which provides the resources to attend to various observables, and by expectations (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995), which interact to guide attention towards various observables present in the environment, discussed in more detail below.

<u>Attention's Influence in the State Assessment Process</u>

Although not explicitly illustrated in the air traffic controller cognitive process framework, *attention* is a resource directed to a cognitive process regarding a particular observable, observation, or state. In addition, attention may be divided via an information sampling scheme between multiple processes or pieces of information (Wickens & McCarley, 2008). Various sources contribute to attention allocation. Attention can be directed based on knowledge of how an observable is presented, how often the observable is presented, and how often the observable is likely to change (Wickens & Flach, 1988). This knowledge is based in long-term memory, discussed later, where their values are seldom to change significantly through time. However, attention resources can be directed differently based on expectations of the current and future states, as expectations play a large role in directing resources to cognitive processes through attention.

<u>Expectation's Influence in the State Assessment Process</u>

Modeled in the air traffic controller cognitive process framework, expectations are developed as future states in the projection process of state assessment, discussed in 4.3.1.5 Projection Process. In addition, planned and executed actions update these future projected states, discussed in 4.3.2.4 Current Plan. These future states may include alternatives based on no controller action, planned controller actions, or executed controller actions, contingencies based on system structure, and uncertainty. Expectations influence cognitive processes in many ways. Expectations can affect whether observables are searched for, if observables are perceived, how observables are perceived, and how observations are comprehended.[11] In addition, expectations help controllers determine when systems have changed. In essence, expectations can increase efficiency of perception and comprehension. The specific means that expectations and attention influence the perception sub-process is through expectation-driven search.

Expectation-Driven Search

The concept of *guided search* shows how top-down factors influence search efficiency by guiding visual attention to likely target candidates (Wickens, Hollands, Banbury, & Parasuraman, 2013). During ATC tasks, controllers must continually scan their displays to update their state awareness.

As discussed, perception is influenced by both attention and expectation. Once perceived, the information is transformed into an observation. Before discussing the mental model within the perception process, a general discussion regarding mental models within the larger context of the air traffic controller cognitive process framework is warranted.

Mental Models

As discussed in 3.1 Human Information Processing, mental models describe cognitive mechanisms that support the generation and maintenance of state awareness as well as the various decision and execution processes (Histon, 2008). Rouse and Morris argue that "mental models are the basis for estimating the 'state' of the system (i.e., estimating state variables that are not directly displayed), developing and adopting control strategies, selecting proper control actions, determining whether or not actions led to desired results, and understanding unexpected phenomena that occur as the task progresses" (Rouse & Morris, 1986). The mental model is used at various levels of abstraction. In fact, Histon stated "working mental models are a controller's cognitive representation of the system, appropriate for the needs of the current task" (Histon, 2008). This thesis posits a mental model for controllers, located in long-term memory, with an abstraction of the controller's mental model of the system used in each major cognitive process to transform inputs to outputs required for the task of the cognitive process.

4.3.1.1.2 Mental Model in the Perception Process

The mental model in the perception process is an internal representation of the physical form of a system, enabling the human to perceive useful information towards the system state. This abstraction of the mental model uses a combination of top-down and bottom-up processes through the visual and auditory channels and knowledge to recognize, identify, classify, or categorize observables into observations (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Wickens,

[11] Much research uses the term 'expectancy' when reference expectations. For example, Wickens et al. presents numerous cognitive interactions with expectancy throughout their research (Wickens, Hollands, Banbury, & Parasuraman, 2013). However, this thesis uses the term 'expectation' for this concept and "expectation-driven biases" when discussing how expectations influence cognitive processes.

Hollands, Banbury, & Parasuraman, 2013). Perceived observables are input to the mental model and are combined with knowledge from long-term memory which provides the information to accomplish the transformation from observable to observation. Attention resources are required to complete this transformation. Also, expectations can influence how the transformation occurs. The outputs of the perception process, *observations*, can be defined as the value or trend of the observable that was actually observed. These observations are the primary input to the comprehension process to form the controller's current state assumption.[12]

4.3.1.2 Comprehension Process

The *comprehension process* of state assessment is represented as the process by which observations are associated with system state variables and their values. The comprehension process is influenced by knowledge from long-term memory, expectations, and attention. A representation of the comprehension process is shown in Figure 4-5, consistent with research conducted by Endsley (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995) and refined through case study analysis.

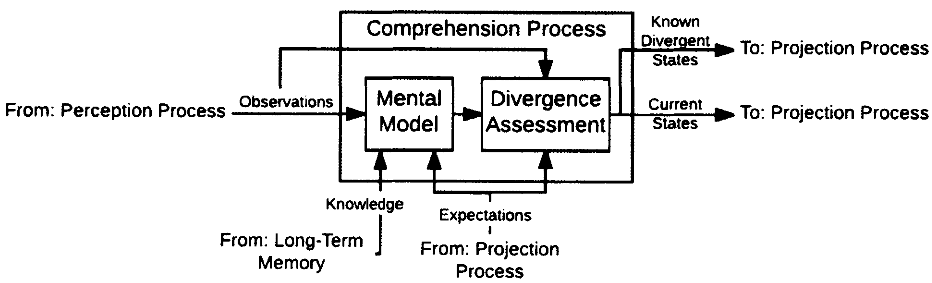

Figure 4-5. Comprehension process representation.

The comprehension process transforms observations to a current state in accordance with the controller's task using an abstraction of the mental model. Also, the comprehension process assesses the certainty of the controller's awareness using observations and expectations in the divergence assessment sub-process.

4.3.1.2.1 Mental Model in the Comprehension Process

The mental model in the comprehension process is an internal representation of the system state, enabling the human to comprehend current system states. The mental model may use a variety of mechanisms to accomplish this. This abstraction of the mental model combines observations with knowledge, expectations, and attention using a combination of association, integration, inference, and frequency

[12] To illustrate the process, an example is given. For instance, during a Conflict Alert (CA) the observables may be considered the light emitted from the TSD and its associated parameters, such as wavelength, intensity, and duration, as well as sound emitted from the headset and its associated parameters, such as frequency, intensity, and duration. If the separate observables are attended to, they may be perceived and sent to the controller's mental model in the perception process. Here, these separate observables will be transformed through the controller's knowledge and expectations to produce separate observations of the letters 'C' and 'A' flashing red on the TSD and an auditory alert 'chirping' in the headset.

gambling (Reason, 1990), to associate and select the current assumed system state. First, one of the primary mechanisms used to relate observations to state variables is by *association*. Reason highlighted the concept *similarity matching* as the primary basis of memory search and defined it as the continuous matching of sensory inputs to attributes of knowledge units stored in memory (Reason, 1990). Here, knowledge is input from long-term memory into the mental model in the comprehension process as shown in Figure 4-5 and discussed further below. However, unique observations are not always correlated with unique states. Therefore, there may be *ambiguous observations*, or observations that can lead to more than one state variable value. For humans to associate states during these periods of ambiguity, the mechanism of frequency gambling, also called *ambiguity resolution* may be employed. Reason describes *frequency gambling* as the mechanism which solves underspecified searches in favor of the most frequently-encountered item, using system statistical properties (Reason, 1990). Statistical properties are gained from knowledge and expectations, which are directed from the projection process, to *infer* a state value. Third, some state variable values require more than one observation for association. A human may have to *integrate* two or more observations to develop a single state value (Reason, 1990). Fourth, some state variables may not associate directly from an observation, but must be inferred by *guessing* based on other information, such as knowledge, expectations, or other state variables and values. Overall, the comprehension process appears to be a complex combination of association, integration, and inference through ambiguity resolution and guessing using observations, knowledge, and expectations to produce current state awareness.[13]

Long-term Memory

Long-term memory is the location of knowledge stores used for recall and recognition that persists through time. The knowledge stored in long-term memory is input to the state assessment process. Proctor and Van Zandt state "an operator must often retrieve information from long-term memory to comprehend current system information and to determine what action is appropriate" (Proctor & Van Zandt, 2008).

4.3.1.3 Divergence Assessment

While the mental model in the comprehension process enables the human to comprehend a current state, the comprehension process also determines the certainty in the human's current state assumption, represented by the divergence assessment process. Silva defined known divergence where the human is

[13] For example, during a CA alarm on a TSD, the separate observations discussed in the previous footnote were the letters 'C' and 'A' flashing red on the TSD and an auditory alert 'chirping' in the headset. The mental model in the comprehension process would associate the visual observations with knowledge gained from training and experience to a 'Conflict Alert.' At the same time, the auditory observation may be ambiguous with other auditory observations, but inferred to be a 'Conflict Alert' due to an expectation of a possible conflict involving two aircraft previously being monitored. The comprehension processes mental model would then integrate these two observations with other TSD observations and previous expectations to associate a state of the algorithm's value of an impending conflict between two aircraft.

aware their state assumption is inconsistent with the actual system state (Silva, 2016). According to Silva, if an expectation is not consistent with an observation, the result is an ambiguous state assumption and known divergence (Silva, 2016). Endsley argues "the main clue to erroneous SA will occur when a person perceives some new piece of data that does not fit with expectations based on his or her internal model" (Endsley M. R., 1995).

As previously discussed, the comprehension process is informed by both observations and expectations when selecting a state. At times, these observations and expectations are in conflict. When they are different, three outcomes can occur. First, the observation may be so strong compared to the expectation that the observation overrides previous expectations and the human has high confidence in their state selection. This often occurs during the normal course of updating state awareness. For instance, when a controller perceives an aircraft out the window in an unexpected position, they may have high confidence that the observation is convergent. Second, the expectation may be so strong compared to the observation it overrides a new observation and the human has high confidence in their previous state selection. For instance, when a controller hears unexpected communication, they may assume the pilot meant something different, something expected. Third, the difference in the current observation and previous expectation leave the human with low confidence in the ability to select a state, leaving that state ambiguous or unknown. For example, when a controller hears a Conflict Alert (CA) but did not expect a conflict they may gather more information before making a determination of whether aircraft are in conflict.

Here, *known divergence* is when the human has awareness that their current state assumption is not consistent with the actual system state. This determination is represented in the divergence assessment process by the comparison of the human's expectation to their observation. When the current state assumption is ambiguous or unknown, the human is in known divergence. The output of the divergence assessment process is a known divergence state 'flag' on particular state variables within the current state assumption. This is an important input to the decision processes, discussed in 4.3.2 Decision Process.

4.3.1.4 Current State Assumption

The comprehension process produces a current state assumption, which is then stored in working memory and updated as appropriate. Many states in the current state assumption come from either an *unambiguous observation*, where the observation was associated or integrated to form a state, or a *selected state* where values were inferred without direct observation in the comprehension process. Regardless, the controller believes these state variable values are consistent with the actual system state. In actuality, these states may be consistent with the actual system state or the controller may be experiencing unknown divergence, unaware of the inconsistency. On the other hand, the controller may be aware that their current state assumption is inconsistent with the actual system state regarding a current state value, which results in either *unknown states* or *ambiguous states*. The controller is diverged, but their divergence is known to them. *Known divergence* can affect downstream cognitive processes. A third component of the current state assumption are *blank states*. Blank states are represented as task relevant states the controller fails to store in working memory; therefore, the controller is experiencing unknown divergence. The controller is unaware of a particular state's relevance and has subsequently not determined its value.

4.3.1.4.1 Working Memory

Working memory is the location of most of a person's active processing of information (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995), and functions to temporarily store and manipulate information (Proctor & Van Zandt, 2008). In the cognitive process framework, working memory is the storage location of the current state assumption and future state projection, which combines to form controller state awareness, and the current plan (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Histon, 2008).

4.3.1.5 Projection Process

The *projection process* of state assessment is the process by which the human's current state assumption is projected into the future and represented by a state vector as a function of time. This process is framed as analogous to a traditional dynamic system described by a state-space (Rowell, 2016). Using this state concept, a mathematical description of a system in terms of the state variables as a function of time $x_i(t)$ can be determined given the initial state variables at a current time $x_i(t_C)$, the system inputs as a function of time $u_j(t)$, and equations describing the system dynamics (Rowell, 2016) shown in Figure 4-6.

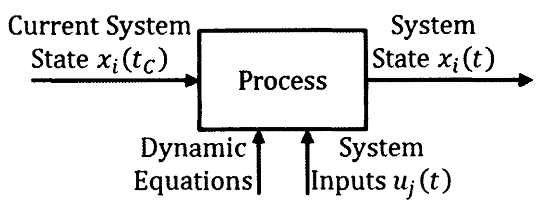

Figure 4-6. Traditional dynamic system.

In the air traffic controller cognitive process framework, the future state projection can be described analogously with the state-space system shown above. The current state assumption is analogous to the current system state, $x_i(t_C)$. Actions developed in the controller's decision processes and stored in the controller's current plan are analogous to the system inputs, $u_j(t)$. Knowledge structures are analogous to the equations describing the system dynamics and input to the controller's mental model within the projection process itself. Combined, these inputs are projected using the mental model in the projection process to produce the future state projection, analogous to the system state, $x_i(t)$. Attentional resources are required to accomplish this projection and the output, future state projection, is stored in working memory. This representation is consistent with Endsley (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995) and was refined through case study analysis, shown in Figure 4-7.

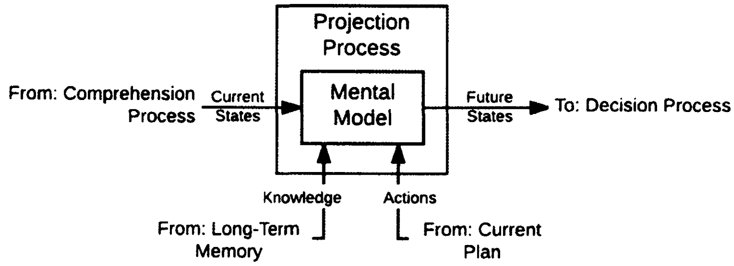

Figure 4-7. Projection process representation.

4.3.1.5.1 Mental Model in the Projection Process

The mental model in the projection process is an internal representation of the system dynamics, enabling the human to project future system states. This abstraction of the mental model combines current assumed states, knowledge, and planned actions using deterministic, probabilistic, linear or non-linear interpolation or extrapolation to produce future projected states. The mental model in the projection process is able to project aircraft positions, environmental situations, abnormal aircraft or other system performance and other states as a function of time.[14]

At times humans understand some of their limitations. Because of these limitations, along with errors and biases within the system, the mental model can also predict various levels of uncertainty of a state value for a given situation. While the controller assumes both current and future states for aircraft under their control, the various levels of uncertainty within these states may depend on a variety of factors. While some states are discrete (e.g. gear up or gear down), others are analog (e.g. velocity). Some states may be directly observed (e.g. gear down by a tower controller), while others are observed through an intermediary (e.g. position by a radar controller), and others are inferred (e.g. intent through a SOP). The development of the mental model includes the understanding of various levels of uncertainty, which may also affect downstream processes such as decision and execution.

4.3.1.6 Future State Projection

The projection process produces a future state projection, stored in working memory and updated as appropriate. Like the current state assumption, a subset of the future state projection consists of *projected states*, states where the controller believes the state variable values are consistent with the actual system

[14] Continuing with the CA example, the current states of the separate aircraft positions, velocities, intent, and the state of the CA alarm timing combine with knowledge of aircraft dynamics and planned actions to produce the aircraft's future position with respect to time. This future projection may include the projected positions of the individual aircraft, their projected separation at point of closest approach, along with a level of uncertainty associated with these values.

state. Similar to the current state assumption, these projected states may be convergent or the controller may be experiencing unknown divergence, unaware of the inconsistency.

Meanwhile, some ambiguous current states can be projected, but the projection process may produce multiple future states values for a single state variable. These *ambiguous future states* are necessarily diverged, but known to be diverged by the controller. Also, some other ambiguous current states and all unknown states cannot be projected. Therefore, these states become *unknown future states* and also produce known divergence. Finally, blanks states are also not projected and continue as blank states, leading to unknown divergence.

4.3.2 Decision Process

The *decision process* is represented as the combined processes used to determine the appropriate response to a situation given the knowledge of the system state (Proctor & Van Zandt, 2008). The decision process in the cognitive process framework consists of the monitoring, evaluation, and planning processes. These three components align with aspects of Pawlak et al.'s (1996) processes required in ATC, used by Histon (2008), but were updated for use within the context of state awareness. A representation of the decision process is shown in Figure 4-8, with the sub-processes presented in the next sections.

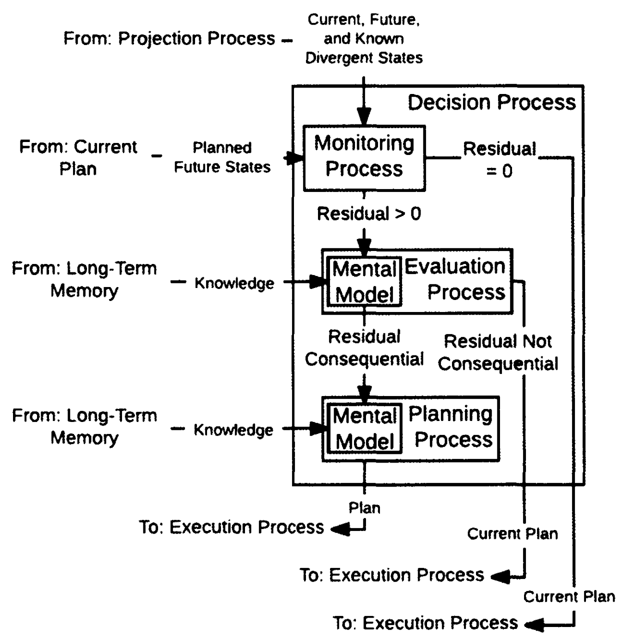

Figure 4-8. Decision process representation.

4.3.2.1 Monitoring Process

The *monitoring process* compares the conformance of controller state awareness against the planned future state from the controller's current plan (Histon, 2008), which was determined in the previous cognitive loop. The output of this process, the difference between these two states, is the *residual*. If the residual is negligible (i.e. residual ≈ 0), controller state awareness and the planned future state from the previous cognitive loop are congruent. In this case, the controller determines that no additional planning is required within the decision process and the current plan is continued. However, if the residual is substantial (i.e. residual $\neq 0$), controller state awareness and the planned future state from the previous cognitive loop are incongruent. A residual may also exist due to known divergence. A non-zero residual will lead to an evaluation process.

4.3.2.2 Evaluation Process

The *evaluation process* is represented to verify the effectiveness of controller state awareness in meeting the controller's goals while abiding by system constraints. The mental model within the evaluation process is an internal representation of the goals and constraints of a system, enabling the human to make value judgments of whether the current and future system states will achieve the goals within the constraints. The mental model seeks to determine if the residual is too large to achieve the controller's goals within system constraints, which would require a new plan to correct. If the residual is below the controller's threshold, no planning is required and the current plan is continued as shown in Figure 4-8. If the residual is above the controller's threshold, planning is accomplished.

4.3.2.3 Planning Process

The *planning process* consists of identifying and scheduling a series of control actions required to meet the goals within system constraints. This is accomplished by the mental model within the planning process, which is an internal representation of the goals, constraints, dynamics of and potential actions on a system, enabling the human to make value judgments and choices of various actions and their resulting future system states. Inputs to the mental model include controller state awareness and the residual. In addition, the mental model receives knowledge of procedures available to the controller to affect the system and knowledge of the system dynamics, similar to the knowledge within the mental model of the projection process, to conduct internal thought experiments (Rasmussen, 1983). This mental model abstraction uses a range of decision-making processes, such as mental simulation, heuristics, utility theory, and naturalistic decision-making, to determine an appropriate response to the situation. While courses of action may be determined through internal thought experiments, as illustrated by Klein's NDM research, humans rarely generate numerous alternative options and compare them for optimality (Klein, 2008). Experts usually use their experience in the form of a repertoire of patterns, matching to suggested courses of actions (Klein, 2008), essentially rule-based behavior (Rasmussen, 1983; Embrey, 2005). Without patterns, knowledge-based behavior is required (Rasmussen, 1983; Embrey, 2005). Regardless, mental simulation may still be required and plans may be modified from stored procedures to create usable actions. The appropriate response is output as planned actions and resultant planned future states.

A distinction of the mental model representation in the planning process is the ability to project future alternatives. Using the conflicting aircraft example, the controller may first project an aircraft's future position along their current flight plan without controller inputs in the projection process, which could be used to determine future aircraft separation. However, as part of the decision processes the controller may also wish to perform internal thought experiments to understand alternative aircraft positions following various controller commands. Rasmussen described "internal thought experiments" as an attempt for a human to reach a specified goal using different mental representations or "mental models" (Rasmussen, 1983). Internal thought experiments can be accomplished using the mental model to understand which commanded actions will best achieve a specified goal, as well as the planned future states following the commanded actions now form the system expectations (Wickens, Lee, Liu, & Gordon Becker, 2004).

Another abstraction of the mental model is its use to predict various contingencies. For instance, the controller may determine the most appropriate course of action with conflicting aircraft is to vector one aircraft to the right. However, the controller may develop a contingency plan in case the first aircraft fails to respond to controller commands. Here, the controller may contact the second aircraft immediately following failed acknowledgement from the first. While an unlikely case, failed communications could have negative consequences, such as a Mid-Air Collision (MAC), if the possibility is not accounted for in the decision process. Therefore, the mental model is posited to contain such contingencies and the probability of their occurrence.

The mental model in the planning process also determines the plan of actions if the controller is in known divergence. Figure 4-9 shows three discrete states of controller awareness, convergence, unknown divergence, and known divergence.

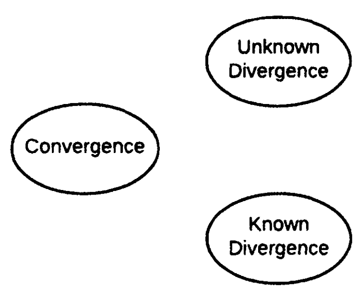

Figure 4-9. Possible discrete states of controller awareness.

When a controller is in known divergence, the controller may work to resolve their divergence by eliciting information from the system. This elicitation includes both passive and active elicitation through visual and auditory channels, including directed visual perception, directed auditory perception, and requests for information through voice or data communication channels. The controller could also command a state through communication channels when in known divergence, such as directing an aircraft's altitude to align their awareness.

4.3.2.4 *Current Plan*

The air traffic controller cognitive process framework represents the output from the decision processes as either a new plan or the previous plan, and uses the concept of the "current plan" as a repository of this information, stored in working memory. The *current plan* is defined as an internal representation of a schedule of planned actions and their resultant planned future states.[15] These planned future states are for nominal conditions, but could also include reasonably possible contingencies. Although the current plan does not process information relating to divergence, it acts as a repository for information input to the state assessment, decision, and execution processes. First, the current plan is a store of planned actions. The primary way a controller affects the system is through the action of communicating commands. However, the controller may execute actions within the facility, such as communicating with other controllers, manipulating their displays, or directing attention to other observables through perception. These series of actions are based on a plan, which may be based on other events or states in the system, based on time, or based on the controller's knowledge of the system itself. Second, the current plan consists of a store of planned future states resulting from controller state awareness and the schedule of planned actions. These planned future states are used as expectations, which are input to various cognitive processes within state assessment. In addition, these planned future states are compared to controller state awareness from the current loop of the cognitive process framework to determine the need to plan, discussed in 4.3.2.1 Monitoring Process. Similar to other information in the cognitive process framework, the current plan may store information at various levels of abstraction and is continually updated.

4.3.3 Execution Process

The *execution process* of the cognitive process framework is represented as the final process to implement an action which can affect the system, shown in Figure 4-10. It can be defined as the mental and physical process used to implement actions (Pawlak, Brinton, Crouch, & Lancaster, 1996). The execution process receives input in the form of a plan from the decision process through the current plan. In addition to plans, knowledge for action execution is input from long-term memory. The mental model transforms knowledge and plans to an action that is executed at the appropriate time based on the plan.

[15] The definition is modified from (Histon, 2008) to reflect the requirements of this thesis. Histon defines the current plan as "an internal representation of the schedule of events and commands to be implemented as well as the resulting trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner."

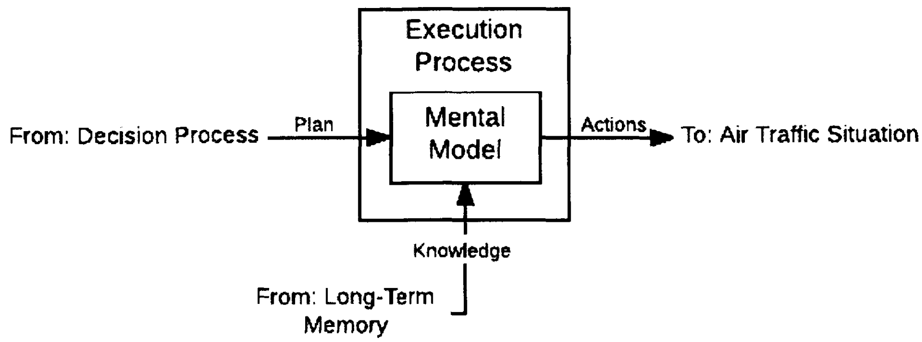

Figure 4-10. Execution process representation.

4.3.3.1 Mental Model in the Execution Process

The mental model in the execution process is an internal representation of the indications to extract information from and the procedures to act on a system, enabling the human to attend to useful information or communicate with system agents. This abstraction of the mental model combines knowledge and planned actions to execute the external or internal actions at the appropriate time and in the appropriate sequence.[16]

[16] Finalizing the example, the mental model receives the planned action to vector one aircraft, and using procedural knowledge to execute, communicates the command to the aircrew. Following this, the controller attends to the observable of the planned future state of an acknowledgement and aircraft trajectory change at the determined time.

5 Framework to Understand the Causes of Divergence

To understand how to minimize divergence in human controllers while they manage a human-integrated system, the causes of controller divergence must be understood. The air traffic controller cognitive process framework provides a means to investigate the possible pathways leading to inconsistent controller state awareness, or divergence, shown again in Figure 5-1. Divergence occurs when the human's current state assumption is inconsistent with the actual system's current state. Divergence also occurs when the human's future state projection is inconsistent with the actual system's future states.

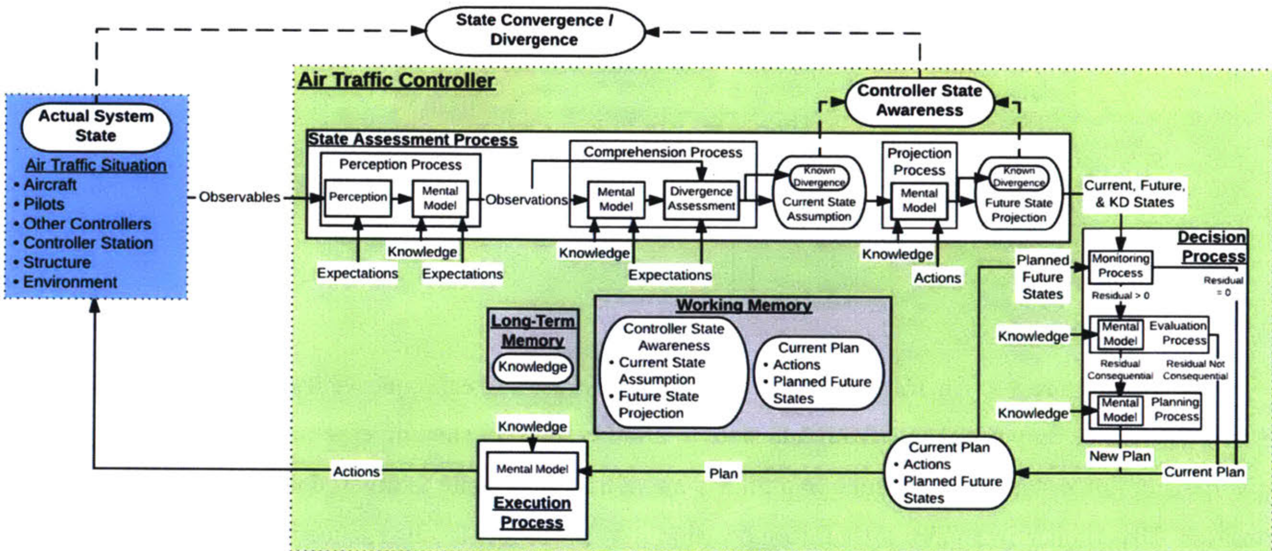

Figure 5-1. Air traffic controller cognitive process framework.

This thesis describes errors leading to divergence as either incorrect information propagated through the controller's state assessment processes or failures of a specific state assessment process or working memory. This differentiates instances of propagation errors when a state assessment process receives incorrect inputs and subsequently fails to provide a correct output versus process failures when a state assessment process receives a correct input yet fails to provide a correct output.

More specifically, divergence can be caused by a lack of or incorrect observables input to the controller's state assessment processes, propagating through the state assessment processes to controller state awareness and divergence. Divergence can also be caused by a failure of the state assessment process to transform or project an accurate observable to a correct current or future state, respectively. Finally, divergence can be caused by a working memory failure that receives a correct state but transforms it to an incorrect one.

At a high level of abstraction the multiple pathways, or causes, of divergence are visually represented in Figure 5-2 as the left-hand side of the air traffic controller divergence cause and consequence framework.

For instance, a perception process failure can cause divergence by propagating through the comprehension process and projection process to provide an incorrect future state to controller state awareness. However, a comprehension failure may cause divergence without additional propagation by providing an incorrect current state to controller state awareness. Observable errors, process failures, and memory failures may propagate to controller state awareness and may be inconsistent with the actual system state from the air traffic situation, leading to divergence.

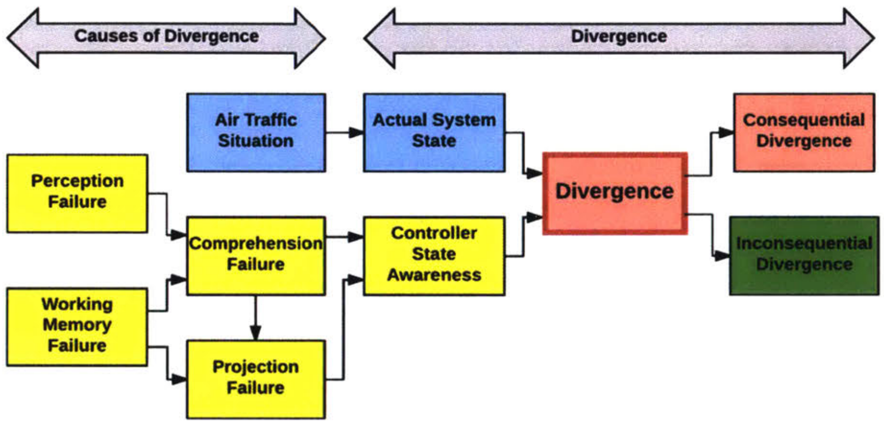

Figure 5-2. Air traffic controller divergence cause and consequence framework.[17]

Also, divergence may propagate from one state to another, current state divergence to future state divergence. For instance, divergence in a pilot's intent may propagate to divergence in an aircraft's future position. Divergence in an aircraft's future position may propagate to divergence in two aircraft's future separation. While multiple variables may constitute the task relevant state, as few as one or possibly many variables within the task relevant state vector may be inconsistent.

Process or memory failures may occur for a variety of reasons and are illustrated using the air traffic controller cognitive process framework in Figure 5-1. Process and memory failures will be described by having a source of the failure, such as a perception process failure occurring due to a lack of perception in the perception sub-process. Also, sources of process failures may have a mechanism causing the source to occur. For instance, an expectation-driven bias (mechanism) may cause a lack of perception (source) in the perception sub-process, leading to a perception process failure and divergence.

5.1 Incorrect Outputs of the State Assessment Process

The cognitive process framework models controller state awareness as an output of the state assessment process, which can lead to divergence by producing an incorrect state when compared to the actual

[17] The blue color within the framework represents the air traffic situation and the actual system state which is consistent with the colors of the cognitive process framework. Yellow represents the various process and memory failures that may lead to an inconsistent state awareness. Red signifies divergence and consequential divergence as the hazardous event investigated in this thesis. Green shows inconsequential divergence as a type of divergence leading to a non-hazardous consequence.

system state. While this process contains feedback, it will be discussed serially and systematically to illustrate specific mechanisms and sources contributing to the process failures and divergence.

5.1.1 Incorrect Outputs of the Perception Process

The perception process can produce incorrect outputs in a variety of ways, including the propagation of incorrect observables, incorrect inputs to the perception process, or internal perception process failures.

5.1.1.1 Incorrect Observable Inputs

One cause of divergence, categorized within observable errors, are the lack of observables available for perception of a task relevant state (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995; Jones & Endsley, 1996; Jones D. G., 1997). This could occur for a variety of reasons. First, the system may not have been designed to provide an observable of a task relevant state (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995). Second, while the system may have been designed to provide an observable, the object producing the observable may have failed (Silva, 2016), such as a display or communication failure. Third, an organizational decision may have inhibited an observable from being provided to the controller. At times these decisions are made based on performance or safety tradeoffs, such as removing an alert with a high false-alarm rate. Fourth, the controller may inhibit an observable based on their personal display settings. For example, many controllers de-clutter MVA values on their TSD.

Another source of observable error is an inaccurate observable. This could occur due to software or hardware malfunctions within the system, or human error propagated through the air traffic situation to an observable perceived by the controller. Incorrect observables could be communicated to the controller in a visual display or voice communication. In fact, pilot divergence can propagate to controller divergence when a pilot communicates their diverged state to the controller as an inaccurate observable.

5.1.1.2 Incorrect Outputs of the Perception Sub-process

An accurate observable may not be perceived by the controller. A lack of perception could occur due to a barrier to perception (Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995), such as a physical barrier blocking the view of a display or an architectural barrier, such as stepped-on transmissions of voice communications to a controller. Also, the controller may not perceive an observable because it may be indiscriminate (Jones & Endsley, 1996).[18] Indiscriminate observables are often due to inadequate controller display settings or a lack of observable salience by system designers. The controller may not perceive observables due to poor attention allocation from human factors

[18] In this thesis indiscriminate includes observables difficult to discriminate from others or difficult to detect.

considerations such as stress, from poor information sampling strategies learned in training or developed through experience, or from expectation-driven biases.

5.1.1.2.1 Attention Issues Leading to Perception Sub-process Failures

Attention can be influenced by human factors such as stress. Stress can be caused by workload, fatigue, social issues, or the environment (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995), and has been shown to negatively affect attentional capacity. Both acute and chronic stress may impair attention allocation, leading to strong distractibility during information selection (Liston, et al., 2006; Sanger, Bechtold, Schoofs, Blaszkewicz, & Wascher, 2014). As workload increases, attention may be forced to shift internally and narrow (Tenenbaum & Connolly, 2008). However, attention can be negatively affected with low arousal levels as well, described by the Yerkes-Dodson law (Proctor & Van Zandt, 2008). Fatigue has been shown to reduce goal-directed (top-down) and stimulus-driven (bottom-up) attention (Boksem, Meijman, & Lorist, 2005; Faber, Maurits, & Lorist, 2012). Fear and time pressure, both social stressors, can negatively impact attention allocation and can occur immediately after events such as alerts or the perception of a potentially hazardous situation. Finally, environmental stressors such as discomfort or noise can cause attention issues.

A failure in attention allocation can lead to a lack of perception of an observable, such as when a poor scan strategy or poor information sampling behavior results in a lack of perception (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995), occurring when the controller has developed a poor technique to receive incoming observables from training or experience. Also distraction can affect controller perception, such as when a controller is distracted with one set of observables and misses another (Reason, 1990; Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995; Silva & Hansman, 2015; Silva, 2016). Expectations can also have an enormous impact on where attention is directed.

5.1.1.2.2 Expectation-Driven Search Bias in the Perception Sub-process

Expectation-driven search bias may lead to not perceiving an observable. Based on their expectations, the controller's scan strategy may fail to attend to an observable. For instance, if a controller does not expect inclement weather at a certain location, they may not attend to an observable which would provide weather state information at that location.

5.1.1.2.3 Expectation-Driven Attention Bias in the Perception Sub-process

Controllers can also fail to perceive observables that fall within their scan if the observable is contrary to expectations (Simons D. J., 2000). Wickens and colleagues say "we can look, but fail to see, even if the unexpected event involves a large, unusual, dynamic object, which is fully visible for several seconds"

(Wickens, Hollands, Banbury, & Parasuraman, 2013). This phenomenon is known as *inattentional blindness*, a subset of *change blindness*.[19] An example of expectation-driven attention bias is when a controller fails to see a primary radar return on their TSD if the pilot has not communicated with the controller, because the controller is not expecting an aircraft within their control responsibility.

In the cognitive process framework, mental models can fail to produce the desired output for a variety of reasons. These include inadequate inputs to the mental model, such as incorrect knowledge learned from training and experience, or can fail by an internal failure of the mental model. Each abstraction of the mental model may internally fail for different reasons and are discussed specifically in each section.

5.1.1.3 Incorrect Outputs of the Mental Model in the Perception Process

Even if the controller perceives an accurate observable, they may produce an inaccurate observation through their mental model. This could occur due to incorrect knowledge input to the mental model. Another mechanism contributing to inaccurate observations is expectation-driven perception bias.

5.1.1.3.1 Expectation-Driven Perception Bias in the Mental Model of the Perception Process

This concept relates to 'top-down' perception and can occur in both the visual and auditory modalities for controllers. In the visual channel, an observable can elicit many distinct patterns of retinal stimulation, depending on viewpoint, lighting conditions, or the interposition of occluding surfaces (Summerfield & Egner, 2009). Expectation-driven perception bias could occur due to incomplete or 'quick' observations or partial barriers to observables. More common in the ATC domain, processing of speech is subject to expectation-driven biases due to invariance, segmentation, and the serial and transient nature of auditory messages (Wickens, Hollands, Banbury, & Parasuraman, 2013). Examples of this include errors in the pilot's repeat of a clearance issued (known as 'readback' error) and the controller's failure to detect and correct errors in the pilot's readback (known as 'hearback' error). A controller may fail to correctly perceive a pilot's incorrect altitude readback because of the strong expectation of compliance.

These four sources of perception process failures can propagate to the comprehension process by outputting either no observation or an incorrect observation. In addition, ambiguous observations can be passed to comprehension, which will be discussed in the comprehension process specifically.

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[19] According to Wickens et al., *change blindness* describes those situations when environment changes are not noticed (Wickens, Hollands, Banbury, & Parasuraman, 2013). A subset of change blindness, *inattentional blindness*, is the failure to notice something when the observer directly looks at it (Wickens, Hollands, Banbury, & Parasuraman, 2013). A common video representation of inattentional blindness is from research by Simons and Chabris partially titled "Gorillas in our Midst," where participants are asked to watch a video of actors playing basketball and count the number of passes between them (Simons & Chabris, 1999). During the video, another actor dressed in a gorilla suit proceeds to walk across the frame, stopping for a moment to beat their chest, and then exits the frame. Over half of participants failed to notice the gorilla (Wickens, Hollands, Banbury, & Parasuraman, 2013).

5.1.2 Incorrect Outputs of the Comprehension Process

The comprehension process produces the controller's current state assumption. This process can produce an incorrect output for a variety of reasons, including propagation of an incorrect output from the perception process, a lack of or incorrect inputs to the comprehension process, or an internal comprehension process failure.

5.1.2.1 Incorrect Observation Inputs

An incorrect, ambiguous, or lack of an observation could propagate through the comprehension process and provide an inconsistent current state. An incorrect observation can propagate via association or integration to an inconsistent current state assumption, or divergence. In addition, no observation or an ambiguous observation can lead to an inconsistent current state assumption, or divergence, due to an inference failure.

5.1.2.2 Incorrect Outputs of the Mental Model in the Comprehension Process

The mental model in the comprehension process can produce incorrect outputs due to inappropriate inputs to the process or internal process failures. First, inappropriate knowledge (incorrect knowledge or lack of knowledge) from long-term memory could associate with observations to form a state leading to an inconsistent current state assumption and divergence (Reason, 1990; Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995; Jones & Endsley, 1996; Jones D. G., 1997; Silva, 2016). For example, a transponder beacon code (e.g. 7600) could be associated with incorrect knowledge (e.g. 7600 = emergency) to form an inconsistent state (e.g. emergency) rather than the consistent state (e.g. loss of communication).[20] Also, inappropriate knowledge may adversely affect statistical properties of an ambiguous observation or no observation, leading to an incorrectly inferred state (Silva & Hansman, 2015; Silva, 2016). Finally, the comprehension process may fail to provide a consistent current state due to an internal mental model failure to associate, integrate, or infer a state. Although incorrect outputs may often be due to inadequate observations or knowledge as described above, expectation-driven biases play a large role.

5.1.2.2.1 Expectation-Driven Comprehension Bias in the Comprehension Process

Expectation-driven comprehension bias refers to accurate observations that are comprehended incorrectly due to expectation's influence on the comprehension process. Although accurate, some observations may

[20] Some discrete transponder beacon codes are designated and associated with specific meaning. For example, '7600' is associated with radio failure and '7700' is associated with an emergency in accordance with FAA JO 7110.65 (Federal Aviation Administration, 2015).

be ambiguous and comprehended incorrectly because of an expectation.[21] Consistent with Reason's frequency gambling, the comprehension process associates probabilities for ambiguous observations using knowledge from long-term memory and expectations to produce a state (Reason, 1990). Therefore, expectations in the comprehension process may result in association errors due to incorrect probabilities of ambiguous observations or low-probability occurrences. In addition, controllers may infer a state based on no observation, but can do this incorrectly due to expectation, similarly to an ambiguous observation as just discussed. Finally, some observations may be unambiguous, but the controller's expectation is so strong it overrides the state associated with the new observation with an expected state. Overall, expectation-driven comprehension bias can be viewed as a possible subset of *confirmation bias*, but within the context of comprehension.[22] For example, a controller may perceive a VFR aircraft on their TSD and comprehend the pilot's intention to remain on its current trajectory due to expectation, because through prior experience the controller has seen this trajectory most often, although the controller has no observation of the pilot's intent.

Incorrect outputs of the mental model in the comprehension process may result in no state assumption, an ambiguous state assumption, or an incorrect state assumption. Diverged states are stored in working memory as the controller's current state assumption, part of state awareness, and passed to the projection process.

5.1.2.3 Working Memory Failure – Current State Assumption

The current state assumption is stored in working memory which can fail and result in the incorrect change of a state and divergence (Reason, 1990; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995). Working memory failures can occur when state awareness fades over time, due to inappropriate attention allocation (Wickens, Hollands, Banbury, & Parasuraman, 2013), when the human requires but does not execute rehearsal to continuously store a state. Working memory failures can also occur due to stress (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995), which acts to decrease the both the capacity and duration of storage in working memory.

States that succumb to working memory failures can transition to a variety of values. For instance, states may transition to *default values*, incorrectly resorting to standard values when others were appropriate

[21] This is different than expectation-driven perception bias where the human does not perceive the observable accurately. For example, they may visualize an aircraft flying away from them because they expected it to, although the aircraft is actually flying towards them. Expectation-driven comprehension bias occurs when the human perceives accurately, but based on expectation comprehends an incorrect state. For example, although they perceive an incorrect communication, they comprehend a different state due to expectations of conformance.

[22] According to Kassin, Dror, and Kukucka, *comprehension bias* is a concept by which people tend to seek, perceive, interpret, and create new evidence in ways that verify their preexisting beliefs (Kassin, Dror, & Kukucka, 2013). Here, expectation-driven comprehension bias refers to how controllers interpret evidence that verify their preexisting beliefs.

(Reason, 1990; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995; Jones & Endsley, 1996; Silva & Hansman, 2015), or the awareness of the state may be lost altogether. These default values may be null, a previous or recent value associated with the variable, an average value, or a common value. In addition, controllers can swap state variable values with ambiguous or otherwise similar state variables, such as the identity of two of the same type of aircraft.

5.1.3 Incorrect Outputs of the Projection Process

The projection process produces the controller's future state projection. This process can produce an incorrect output for a variety of reasons, including propagation of a diverged current state assumption, a lack of or incorrect inputs to the projection process, or internal projection process failures.

5.1.3.1 Incorrect Current State Assumption Inputs

An incorrect, or diverged, current state assumption, in the form of no current state, an incorrect current state, or an ambiguous current state, could propagate to an incorrect output of the projection process and future state projection divergence. Whether the current states are projected, which can occur with an inconsistent current state or some ambiguous current states, or not projected, which occurs with no current state or some ambiguous current states, these inputs are likely to lead to diverged future states. As seen in Figure 4-6, when initial conditions are incorrect, the likelihood of an incorrect final condition increases. Conversely, a consistent current state can be passed but incorrectly projected within the mental model of the projection process.

5.1.3.2 Incorrect Outputs of the Mental Model in the Projection Process

The mental model in the projection process could provide incorrect outputs in two primary ways, either from an inappropriate input or an internal mental model failure in the projection process itself. First, the projection process could provide an incorrect output due to incorrect knowledge inputs from long-term memory to the mental model. Here, the controller may not have the required knowledge for the agent or system dynamics in question, leading to an inability to project. Or, the controller may utilize incorrect knowledge for a given situation (Jones & Endsley, 1996), which could result in an incorrect state projection. One example of incorrect knowledge is in the form of default values, which are developed by the controller over time (Endsley, Bolte, & Jones, 2003). Unfortunately, these default values may persist even after updated observables have been perceived, continuing to corrupt the projection (Reason, 1990; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995; Jones & Endsley, 1996; Silva & Hansman, 2015). Also, although controller actions are an input to the projection process, this thesis categorizes inappropriate actions as incorrect propagated values from another process or store, such as previous divergence.

Second, the projection process could fail due to an internal mental model failure. This thesis categorizes these as mental simulation failures, or the inability to accurately project future states based on consistent and accurate inputs. The reasons for mental simulation failures could be due to ability, training, or experience (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Jones & Endsley, 1996). Humans have inherent limitations projecting into the future. These include biases due to distance, velocity, acceleration, adaptation, and projection timespan (Davison Reynolds, 2006).

Incorrect outputs of the projection process result in no state projection or an inconsistent state projection, both divergence, stored in working memory as the controller's future state projection and passed to the decision processes. In addition, the controller may be aware their future state projection is inconsistent with the actual system state, and therefore be in known divergence regarding future states. This could occur either due to ambiguous or unknown current states propagating to the projection process, a known lack of knowledge input to the projection process, or the known inability to accurately project a future state due to complexity within the mental model in the projection process. Regardless of why known divergence occurs, this may affect downstream cognitive processes by differences in planning. With known diverged future states, the controller may choose to wait before additional state projection and decision making occurs anticipating the ability to more accurately project these states in the future. On the other hand, the controller may elicit information from the system regarding uncertainties in these future states.

5.1.3.3 Working Memory Failure – Future State Projection

Working memory failures occur in future state projection similarly as described in 5.1.2.3 Working Memory Failure – Current State Assumption, resulting in a loss of a previously converged state (Reason, 1990; Endsley M. R., A Taxonomy of Situation Awareness Errors, 1995), and for the same reasons.

The incorrect outputs described in this chapter produce diverged current state assumptions and future state projections, which together form controller state awareness.

6 Framework to Understand the Consequences of Divergence

To understand how to minimize hazardous consequences, the cognitive process framework provides a model to investigate the possible consequences, or controller actions, resulting from divergence. The air traffic controller divergence cause and consequence framework shown in provides a visual representation of how the controller's actions following divergence affect the system they are controlling, shown in Figure 6-1. As discussed, divergence can be categorized as either consequential or inconsequential. Consequential divergence will lead to a hazardous action, decomposed as either "no action" or an "incorrect action," leading to a potentially hazardous situation. This will propagate to a hazardous consequence unless mitigated by the controller through their transition from unknown divergence to re-convergence and a correct recovery action or mitigated by the system to a non-hazardous consequence. In addition, the framework can be used to identify and understand potential mitigations for divergence consequences, discussed later.

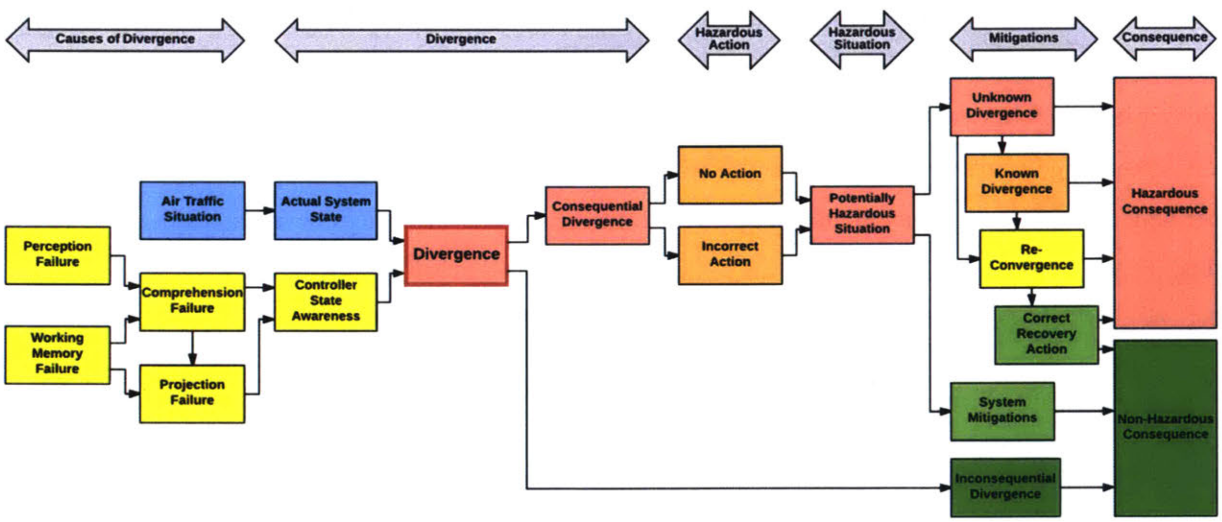

Figure 6-1. Air traffic controller divergence cause and consequence framework.[23]

6.1 Consequential and Inconsequential Divergence

Consequential divergence is divergence which is substantial enough in a task relevant state and a consequential situation to affect the outcome of a situation. This thesis is concerned with consequential divergence, its causes and consequences, along with identifying mitigations for both.

Inconsequential divergence is divergence which is either not substantial enough, not in a task relevant state, or not in a consequential situation to affect the outcome of a situation. It is hypothesized controllers experience inconsequential divergence often during their duties. However, because it is inconsequential, it

[23] Orange represents the hazardous actions which propagate consequential divergence to a potentially hazardous situation, shown as red to highlight the hazard.

leads to a non-hazardous consequence rather than a hazardous consequence. An example of inconsequential divergence due to it not being substantial is when a controller is diverged on aircraft velocity by only 10 knots groundspeed. This divergence may not lead to a hazardous consequence because of its small magnitude. Also, inconsequential divergence due to a non-task relevant state could occur when a controller is not aware of the aircraft type they are controlling. Although diverged, it may be inconsequential. Finally, a diverged controller may not be aware of an aircraft's existence. While at times this divergence could be consequential, if the aircraft is not in a consequential situation no hazardous consequence can occur, therefore the divergence is inconsequential. Divergence consequentiality is defined by the state and extent of divergence and the situation.

The distinction between consequential and inconsequential divergence is important because it provides designers a potential means to mitigate the consequences of controller divergence. If designers can transform previously consequential divergence to inconsequential divergence, the divergence will not result in hazardous consequences. The three criteria of divergence consequentiality and potential mitigations are discussed in 6.4.3. However, consequential divergence will propagate through controller cognition to a hazardous action.

6.2 Hazardous Actions

Controller divergence propagation to a hazardous action is presented in the cognitive process framework by the decision and execution processes. These processes receive controller state awareness and transform it to plans and actions as shown in Figure 6-2.

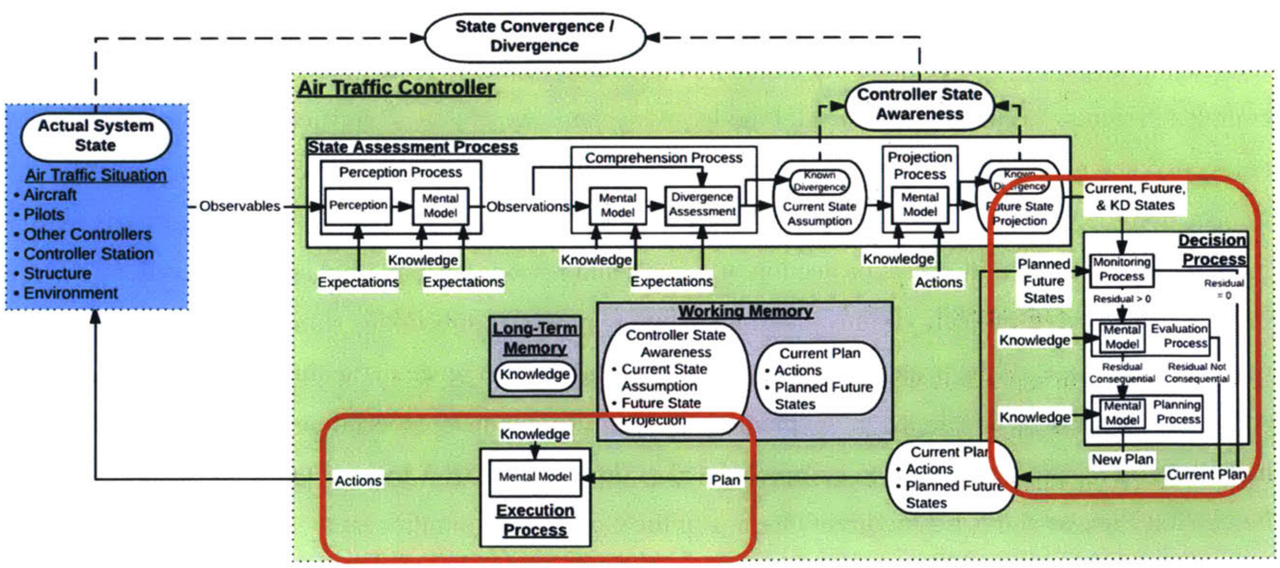

Figure 6-2. Decision and execution processes in the air traffic controller cognitive process framework.

6.2.1 Decision and Execution Process Consequences

The *decision process* consists of the monitoring, evaluation, and planning processes to determine the appropriate response to a situation given knowledge of the system state. Each process propagates diverged states, leading to a current plan which is the consequence of controller divergence. The *execution process* then may implement a hazardous action based on the diverged state awareness that has propagated to it. Although there are other failures of the decision and execution processes within the category of human error, many of these are beyond the scope of this thesis. However, a few factors relating to the monitoring and planning processes will be highlighted below.

6.2.1.1 Monitoring Process Consequences

Since both monitoring process inputs (current and future states from state assessment and planned future states from the current plan) are stored in working memory, working memory failures can cause complete loss of awareness of some state variables. The loss of state awareness and planned future states from prior cognition may lead to a zero residual. For example, if a controller forgets an aircraft's existence, it may affect both controller state awareness and the planned future state from prior cognition simultaneously. This would lead to a zero residual rather than a non-zero residual as expected with a state change from the previous cognitive loop. Therefore, the current plan would continue, possibly leading to a hazardous consequence if the forgotten aircraft is in a consequential situation.

6.2.1.2 Planning Process Consequences

During the planning process, the controller determines the best course of action to resolve the situation (Pawlak, Brinton, Crouch, & Lancaster, 1996). In attempting to understand human interaction with complex systems, Sterman argued mental models of systems are "vastly simplified," "dynamically deficient," and people "fail to appreciate time delays between action and response and in the reporting of information" (Sterman, 1994). Therefore, the knowledge of dynamics from long-term memory can be inaccurate and result in incorrect projection of actions and responses from other agents, specifically incorrect future state projection. This incorrect planning process projection is similar to mental simulation in the mental model of the projection process and can lead to divergence in the future state projection. Also, the future states developed in the planning process contribute to expectations, which can influence how observables are perceived and comprehended as discussed in 5.1.1 Incorrect Outputs of the Perception Process and 5.1.2 Incorrect Outputs of the Comprehension Process.

6.2.2 Decision and Execution Consequences to the Cause and Consequence Framework

Based on the decision and execution consequences discussed earlier, logically developed alternatives for ATC situations, literature, and case study analysis, two hazardous actions were considered. The controller may execute either "no action" or an "incorrect action" that are considered hazardous as shown in Figure 6-1. Leveson (2011) argued for four hazardous control actions within a controlled system.

1. A control action required for safety is not provided or is not followed.
2. An unsafe control action is provided that leads to a hazard.
3. A potentially safe control action is provided too late, too early, or out of sequence.
4. A safe control action is stopped too soon or applied too long (for a non-discrete control action).

The system may or may not require a control action from the controller. From this, a series of logically developed hazardous action possibilities was developed.

The first set of possibilities occurs when a controller action is required to prevent a hazardous consequence from occurring. Analogous to Leveson's (2011) first possibility, the control action required is not provided, or "no action" is executed. The prototypical situation for this hazardous action involves the controller not aware a potentially hazardous situation has developed, and therefore, provides no action to mitigate it. For instance, an impending conflict between two aircraft occurs but the controller does not project the conflict. This could occur due to failed awareness of a potentially hazardous situation or the lack of awareness of their mitigation responsibility.

Also while an action is required, analogous to Leveson's (2011) second possibility, an "incorrect action" is executed. The prototypical situation for this hazardous action involves controller awareness of a potentially hazardous situation, but the lack of awareness the controller's actions will fail to mitigate it. For instance, during the impending conflict mentioned earlier, the controller may project the conflict but incorrectly project their plan of action will mitigate it.

When an action is required, a late, early, or out of sequence control action may be provided, analogous to Leveson's (2011) third possibility. For this thesis, these control actions are considered either "no action," in the case of a late control action, or an "incorrect action," in the case of an early or out of sequence control action. Also, Leveson's (2011) fourth potentially hazardous control action regarding an otherwise safe control action stopped too soon or applied too long rarely applies to ATC due to the discrete nature of most commands passed from the controller to the aircrew.

The second set of possibilities occurs when no controller action is required to prevent a hazardous consequence from occurring. Here, analogous to Leveson's (2011) first potentially hazardous control, "no action" would produce a safe state and does not apply. Analogous to her second potentially hazardous control action (Leveson N. G., 2011), an "incorrect action" may be executed. The prototypical situation for this hazardous action is the lack of awareness the controller's actions would result in a potentially hazardous situation that did not previously exist. In other words, the controller produced the potentially hazardous situation with their incorrect actions. The third and fourth potentially hazardous control actions result in the same discussion as above. Regardless of the type of hazardous action the controller executes, the system is now in a potentially hazardous situation.

6.3 Potentially Hazardous Situation

Following the controller's hazardous action of "no action" or an "incorrect action," a potentially hazardous situation exists as in Figure 6-1. A *potentially hazardous situation* is defined as a situation that could lead to a hazardous consequence unless mitigated. At this point in the event timeline, the system will propagate to a hazardous consequence unless a recovery action is taken. For example, when two aircraft are in future conflict, they will collide unless mitigation occurs, such as a controller vectoring aircraft away from each other or aircrew maneuvering to avoid one another. Although the temporal aspects of divergence and its consequences were not directly investigated in this thesis, the duration between divergence and the hazardous consequence may vary considerably.

The potentially hazardous situation is analogous to the hazardous event traditionally used in bowtie method diagrams discussed in 3.4 Risk Analysis and Accident Causation. However, using divergence as the hazardous event allows the focus directly on divergence and the causes and consequences of divergence are easily represented. Also, the down-stream cognitive processes and controller physical actions following state assessment are consequences potentially mitigated following divergence.

6.4 Mitigations for the Consequences of Divergence

Within the cause and consequence framework following a potentially hazardous situation there are three methods to mitigate hazardous consequences. First, the controller could transition from unknown divergence to re-convergence and execute a correct recovery action enabling a non-hazardous consequence. Second, the system could provide mitigations enabling a non-hazardous consequence to occur. Again, the system is considered everything within the air traffic situation beyond the controller under consideration. Third, the controller divergence could be made inconsequential in some way, enabling a non-hazardous consequence by definition.

6.4.1 Controller Mitigations for the Consequences of Divergence

For the controller to mitigate the consequences of divergence they must command a correct recovery action. There are a variety of pathways propagating from unknown divergence to hazardous or non-hazardous consequences, shown in Figure 6-3.

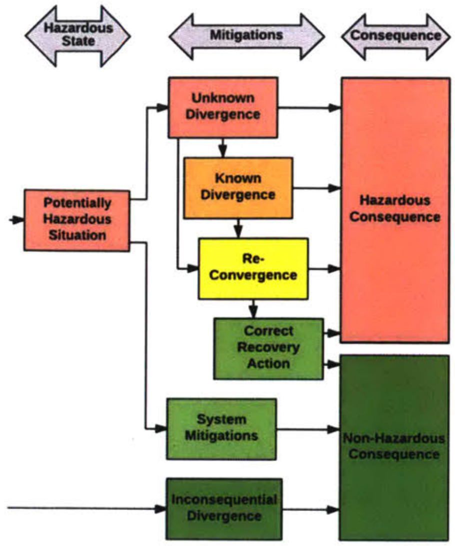

Figure 6-3. Controller mitigations for the consequences of divergence.

First, the controller may remain in unknown divergence until the hazardous consequence occurs, failing to mitigate the hazardous consequence as shown in the pathway from unknown divergence to hazardous consequence in Figure 6-3. As stated earlier, the temporal variety of ATC situations likely plays a factor in how often potentially hazardous situations lead to hazardous or non-hazardous consequences. The lack of transitioning to known divergence or re-convergence can be investigated and potentially mitigated using the cognitive process framework as described with original divergence, discussed in 5.1 Incorrect Outputs of the State Assessment Process.

Second, the controller may transition to known divergence from unknown divergence after a hazardous action. However, the controller may remain in known divergence, failing to mitigate the hazardous consequence as described earlier and shown in the pathway from known divergence to hazardous consequence in Figure 6-3.

Third, the controller may transition from unknown or known divergence to re-convergence in a variety of ways. A newly provided or perceived observable can immediately re-converge the controller. Or, an observable could transition the controller to known divergence, where the controller elicits information to re-converge their state. Although re-converged, the controller could still fail to provide a correct recovery action for a multitude of reasons, leading to a hazardous consequence as shown in Figure 6-3. There may not be enough time available to accomplish an action. There may be no means to communicate the correct recovery action to the aircrew. The system may already be 'unrecoverable,' meaning although the hazardous consequence has not yet occurred, it is imminent.

Fourth, now the controller is re-converged and providing a correct recovery action; however, the hazardous consequence may still occur as shown in Figure 6-3. The hazardous consequence could still occur for the same reasons as previously described, such as not enough time for the aircrew to implement the recovery action, failed communication, or an unrecoverable system. This is analogous to Leveson's (2011) "a potentially safe control action is provided too late, too early, or out of sequence" described earlier.

Fifth, the controller provides a correct recovery action resulting in a non-hazardous consequence as shown in Figure 6-3. The goal of system design is to promote controller re-convergence and correct recovery actions as quickly as possible following divergence. As Silva (2016) highlighted in her research, "The time between recovery and impact for the accident cases, and the time to successfully recover in the incident cases alludes to the accident crew effectively 'running out of time' to recover the aircraft." The controller transition colors in Figure 6-3 are meant to illustrate the trend from most to least dangerous (red → orange → yellow → green), as the mitigations are all shown in green.

6.4.1.1 State Awareness Transitions

During a divergence incident with subsequent re-convergence, the typical transition of state awareness is shown in Figure 6-4 and represented in text below:

Convergence → Unknown Divergence → Known Divergence → Re-convergence

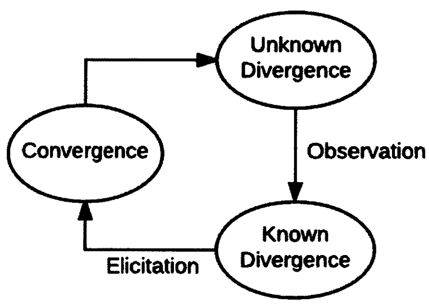

Figure 6-4. Typical transition of state awareness.

Here, following the original unknown divergence, the controller transitions to known divergence within the state assessment process. The transition to known divergence is accomplished by a new observation perceived by the controller. When in known divergence, the controller changes their decision and execution processes to transition to re-convergence through elicitation of information by visual scanning, aural communication, or other means. Although more rare, the controller could command a state to re-converge with the actual system, for instance commanding a vector when the aircrew's current heading is unknown. However, during re-convergence the controller may be uncertain in their state awareness. This can inform the controller's decision processes to elicit more information, let the situation settle, or act conservatively.

Controllers may also re-converge without proceeding through known divergence, as shown in Figure 6-5 and the text below. For instance, if the controller is constantly monitoring an aircraft and immediately perceives and comprehends an unexpected maneuver, the transition may not include known divergence, or at least only known divergence for very short moments in time irrelevant for the cognitive process framework. This case does not affect the decision or execution processes directly, but the controller re-converges through the state assessment processes without eliciting information.

Convergence → Unknown Divergence → Re-convergence

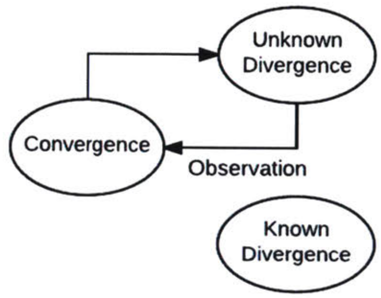

Figure 6-5. Re-convergence without typical lengths of known divergence.

6.4.2 System Mitigations for the Consequences of Divergence

If the controller remains diverged or fails to provide a correct recovery action with enough time to mitigate hazardous consequences, the system should ideally remain robust to divergence by mitigating hazardous consequences despite the controller. System mitigations can take many forms and depend on the specific hazardous consequence and air traffic situation in question. System mitigations can include caution and warning systems onboard aircraft. For example, TCAS has been implemented onboard aircraft to prevent MAC in the event of a Loss of Standard Separation (LoSS). System mitigations can also include procedures to eliminate or reduce hazardous consequences following potentially hazardous states. For instance, pilot visual right-of-way rules for maneuvering during an impending conflict are in place and depend on aircraft category and collision geometry. Shown in Figure 6-6 and according to 14 CFR 91.113, the aircraft to the other's right has the right-of-way when two aircraft of the same category are encroaching on each other's flight path (Code of Federal Regulations, 2016).

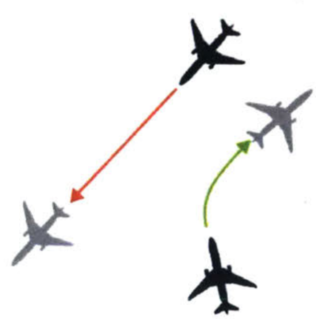

Figure 6-6. Aircraft right-of-way rules (planefinder, 2017).

System mitigations also include other human agents. For example, aircrews maintain Visual Look Out (VLO)[24] to mitigate MAC and Controlled Flight Into Terrain (CFIT) despite being controlled by ATC. In fact, aircrews are the final authority for flight safety. Also, supervisors, coordinators, and assists can override hazardous actions or attempt to prevent a potentially hazardous state during safety critical situations. This redundancy is built into the system because of the knowledge of human error.

6.4.3 Mitigations to Make an Otherwise Consequential Divergence Inconsequential

While less likely than controller or system mitigations, there may be ways to make an otherwise consequential divergence inconsequential. Inconsequential controller divergence will ultimately lead to a non-hazardous consequence with respect to the controller's contribution to the final consequence. To be inconsequential, the divergence must fail to meet one of the three criteria in the definition of consequential divergence. Either the divergence is not substantial enough, not in a task relevant state, or not in a consequential situation, transforming consequential divergence into inconsequential divergence. First, the extent of the divergence could be reduced, but divergence is turned inconsequential this way by mitigating the causes of divergence. Second, the state could be eliminated from the task relevant state vector. For example, aircraft maneuverability could be eliminated from the task relevant state vector if all aircraft maneuvered the same. Third, designers could reduce the likelihood that divergence could result a consequential situation. For example, ATC systems could prevent hazardous actions to be communicated to pilots by integrating communication architecture (e.g. CPDLC) and automation designed to identify conflicts based on controller commanded actions. Another approach may be the increased use of procedural segregation to deny aircraft the ability to interfere with each other, such as the current use of flight levels for direction of IFR flight. These three levers allow designers to reduce the likelihood of a hazardous consequence propagating from controller divergence.

6.5 Final Consequences

During an event the final consequence is either hazardous or non-hazardous. In the ATC case study, a hazardous consequence is analogous to an aircraft accident or incident. The 49 CFR 830.2 states an aircraft accident is "an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage" (Code of Federal Regulations, 2017). An aircraft incident is "an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations." (Code of Federal Regulations, 2017). A non-hazardous consequence is analogous to no aircraft accident or incident.

[24] VLO includes scanning techniques that are important mitigation for aircraft, terrain, and obstacle conflicts.

Although controller and system mitigations are addressed separately, these may occur simultaneously during an event. In addition, hazardous consequences vary in levels of hazard. For instance, an accident is stratified higher than an incident, although both are considered a hazardous consequence in this thesis. Mitigation may reduce a MAC to a Near Mid-Air Collision (NMAC) or LoSS. While all three categories are a hazardous consequence, mitigations should attempt to reduce one to the other.

7 Air Traffic Control Case Study Methodology

The air traffic controller divergence cause and consequence framework and the air traffic controller cognitive process framework were utilized as tools to understand the causes and consequences of controller divergence in historical ATC accident and incident case studies. This approach yielded insight to the causes and consequences of divergence and potential mitigations to reduce controller divergence and divergence consequentiality in the existing ATC system. This chapter will provide the background for case study analysis, the method used to obtain the dataset, the method used to analyze the dataset, and an example case study analysis.

7.1 Background

Aviation accidents and incidents were used as 'cases' in a case study analysis. This type of analysis was conducted due to the complex nature of divergence and its many possible causes, along with the importance of the context in which divergence occurs. Case studies are a valuable research method when 'how' or 'why' questions are being posed because the links requiring analysis must be traced over time (Yin, 1984). In addition, the complexity, detail, and nuance of aviation accidents and incidents in real-life context lend themselves to case study analysis over other methods (Reason, 1990). Finally, case study methods have been used for similar research such as pilot divergence with auto-throttle systems (Silva, 2016), classification of human error leading to commercial aviation accidents (Wiegmann D. A., 2001), human error analysis in general aviation accidents (Wiegmann, et al., 2005). Case studies are also common in the field of psychology (Yin, 1984).

7.2 Accident and Incident Case Studies of Controller Divergence

To effectively analyze divergence the research sought aviation accidents and incidents where potential controller divergence appeared to contribute to the situation's outcome. The unit of analysis was a single accident or incident and analysis was replicated using a multi-case study (Yin, 1984).

To identify potential cases the National Transportation Safety Board (NTSB) Aviation Accident Database and Synopses from 2011 to 2015 were used (NTSB, 2016). This database contains accidents and selected incidents within the US from 1962. Information for each case was obtained from the synopsis, full narrative, final report (NTSB, 2016), docket contents (NTSB, 2016), Aviation Accident Report (AAR) if available (NTSB, 2016), and NTSB Safety Recommendations if available (NTSB, 2017).

The dataset was focused to potential cases of ATC controller divergence by searching the 'ATC' (code 62) and 'ATC personnel' (code 31) modifier codes. These modifiers are the only two related to controllers and were coded by the investigators for each accident or incident (Floyd, 2016). This resulted in a dataset of 52 cases between 2011 and 2015.

These 52 cases were evaluated for potential controller divergence. The preliminary analysis included reviewing the case data and identifying instances of divergence and its primary cause. Ten (10) of these 52 cases did not contain sufficient information to determine if controller divergence occurred, leaving 42 'reviewable' cases in the dataset. Preliminary analysis also determined a number of cases where controller divergence did not occur. The results of the reviewable cases are shown in Figure 7-1.

Figure 7-1. Case study preliminary analysis decomposition (N=42).

Of the 42 reviewable cases, 27 (approximately 64 percent) involved controller divergence. This highlights the significance of controller divergence within the conversation of controller error. Controller decision errors accounted for the accident or incident in 10 of the 42 reviewable cases. Here, the controller was converged, but developed a poor plan despite their converged state awareness which led to an accident or incident. Interestingly, 4 of these 10 cases involved the distribution, or lack thereof, of weather information to the aircrew. Also, 2 cases involved poor ATC procedures. Here, the controller was converged, but poor ATC procedures led to incidents. Both of these cases involved identical go-around operations from intersecting runways at Las Vegas International Airport. Finally, 3 cases were coded as miscellaneous. Of these, 1 case involved a controller who was asleep on duty, 1 case involved an ATIS error occurring the previous day, and 1 case involved no apparent ATC error.

The final dataset analyzed in this research consisted of the 27 cases involving controller divergence as previously mentioned. These cases were sufficient to accomplish the objectives and included a variety of divergence causes and consequences. The dataset of cases analyzed is shown in Table 7-1 and includes the following information:

- Thesis case number (the number referenced within the thesis)
- Date of the accident or incident
- NTSB accident number (the number for reference in all applicable NTSB databases)
- Aircraft involved in the accident or incident
- Description of the accident or incident
- Hazardous consequence (i.e. the result) of the accident or incident

Table 7-1. Case dataset (N=27).

Case №	Date	NTSB Accident №	Aircraft	Description	Result
1	20-Jan-11	OPS11IA246	Boeing 777 & 2x C-17	Controller-to-controller mis-communication of coordinated altitude	2x NMAC
2	11-Mar-11	OPS11IA410	Boeing 777 & 3 other aircraft	Controller lost aircraft awareness during departure	3x LoSS
3	13-Apr-11	OPS11IA476	Beechcraft 300 & 2x T-1	Controller provided an improper pattern sequence	NMAC
4	18-Apr-11	OPS11IA499	Boeing 737 & C-17	Controller provided inadequate wake turbulence separation	LoSS
5	16-May-11	OPS11IA552	Bombardier CRJ-2 & Embraer ERJ-145	Controller provided takeoff clearance with conflicting traffic on final apporach	LoSS
6	14-Jun-11	OPS11IA653	Beechcraft 1900 & Piper Navajo	Controllers provided inadequate separation instructions	NMAC; Vectors below MVA
7	19-Jun-11	OPS11IA673	Cessna 172 & Embraer ERJ-145	Controller cleared two aircraft for takeoff simultaneously	NMAC
8	08-Aug-11	OPS11IA819	Embraer ERJ-135 & Embraer ERJ-145	Controller provided takeoff clearance with conflicting traffic on final apporach	NMAC
9	14-Oct-11	OPS12IA041	2x Cessna 172	Controller failed to mitigate a wrong runway takeoff	LoSS
10	03-Nov-11	OPS12IA122	Boeing 717 & Boeing 757; Boeing 757 & Boeing 767	Controller provided inadequate separation to aircraft within the radar pattern	2x LoSS; Vectors below MVA
11	01-Dec-11	OPS12IA167	Boeing 737 & LearJet 45	Controller provided inadequate separation during takeoff/taxi operations	NMAC
12	06-Mar-12	DCA12PA049	Kfir	Controller failed to provide weather conditions to aircrew	Fuel exhaustion
13	10-May-12	DCA12FA069	Airbus 319	Controller lost awareness of injured occupants onboard aircraft	Lack of medical support
14	22-Jun-12	ERA12FA409	Beechcraft 90	Controller failed to provide a safety alert to the pilot	CFIT
15	31-Jul-12	OPS12IA849	EMB-135 & EMB-170; EMB-135 & EMB-170	Controller-to-controller mis-communication of runway in use	2x LoSS
16	28-Oct-12	ERA13LA042	Piper PA-32	Controller provided vectors below MVA	CFIT
17	16-Dec-12	ERA13FA088	Piper PA-28	Controller provided inappropriate handling of an emergency aircraft	Loss of control in flight
18	04-Jan-13	ERA13FA105	Beechcraft 35	Controller provided inappropriate handling of an emergency aircraft	Engine failure
19	08-Mar-13	ANC13FA030	Beechcraft 1900	Controller provided an inadequate clearance and failed to monitor an aircraft on approach	CFIT
20	12-Jan-14	DCA14IA037	Boeing 737	Controllers provided an inadequate airport pointout and failed to monitor an aircraft on approach	Landed at wrong airport
21	11-Apr-14	ERA14FA192	Piper PA-32	Controller provided inappropriate handling of an emergency aircraft	Loss of control in flight
22	24-Apr-14	OPS14IA005	Boeing 737 & Embraer ERJ-145	Controller provided takeoff clearance with conflicting traffic on final apporach	NMAC
23	15-Aug-14	OPS14IA011	Boeing 747 & Boeing 777	Controller provided conflicting trajectory commands enroute	LoSS
24	23-Oct-14	ERA15FA025	Cirrus SR-22 & Helicopter	Controller provided conflicting commands in the traffic pattern	MAC
25	07-Jul-15	ERA15MA259	Cessna 150 & F-16	Controller provided inadequate separation services	MAC
26	16-Aug-15	WPR15MA249	Cessna 172 & North American NAR-265	Controller provided conflicting commands in the traffic pattern	MAC
27	07-Sep-15	ERA15FA340	Beechcraft 36	Controller provided inappropriate handling of an emergency aircraft	Loss of control in flight

7.3 Case Study Research Method

To understand the causes and consequences of controller divergence in ATC accidents and incidents, the following steps were taken in each case and accomplished by a subject matter expert based on NTSB investigation data and findings.[25]

Step 1. Identify divergence, divergence type, divergence state, and re-convergence
Step 2. Identify the causes of divergence
Step 3. Identify the consequences of divergence
Step 4. Identify potential mitigations

To analyze each accident or incident, material was obtained as described in 7.2 Accident and Incident Case Studies of Controller Divergence.[26]

7.3.1 Step 1 – Identify divergence, divergence type, divergence state, and re-convergence

To identify divergence, the actual system state and controller state awareness were determined. Actual system state was determined through NTSB investigation data, specifically provided from sources such as Flight Data Recorders (FDR) and Cockpit Voice Recorders (CVR), Airport Surveillance Radar (ASR) data, along with other NTSB investigation findings from pilot and controller interviews, reports, and testimonies. At times, graphic depictions of the flight route or relationships between aircraft were available on charts, maps, or display overlays. For example, Figure 7-2 was presented in case #8 within the ATC Group Chairman Factual Report showing an Airport Surface Detection Equipment Model X (ASDE-X) screen capture of the geometry of two aircraft in conflict with each other, highlighted with red and orange circles.

Figure 7-2. ASDE-X screen capture (National Trasnportation Safety Board, 2012).

[25] Subject matter expert qualifications are briefly highlighted in Appendix G.
[26] There were no NTSB AARs in the final dataset. Also, not all aviation investigations result in safety recommendations. Case #17, 18, and 21, along with case #25 and 26 resulted in two NTSB Safety Recommendation Reports. The NTSB docket may have included facility recommendations which were discussed as appropriate.

Also, communication transcripts provided actual system state of communications between controllers and aircrew. An example of a small transcript excerpt given in the NTSB docket contents of case #17 is presented.

1957:20	ER	november one four whiskey ah are you able direct zodgi
1957:27	N5714W	ah direct ah which one sir
1957:30	ER	the initial approach fix runway four are you able to navigate direct zodgi
1957:34	N5714W	(unintelligible)
1957:39	ER	and one four whiskey ah turn right heading zero five five and join the final approach course report established over

Figure 7-3. Communication transcript (Federal Aviation Administration, 2013).

Controller state awareness was primarily determined from the ATC Group Chairman Factual Report, although at times were annotated in separate controller interviews or statements attached in the NTSB docket. Regardless, controller testimony was the primary source of data to determine controller state awareness and was provided through statements such as 'I thought,' 'I saw,' 'I heard,' 'I expected,' or similar statements alluding to what the controller perceived, comprehended, or projected regarding the task relevant system states. If required, controller state awareness could be inferred by the actions executed and control SOPs because of the structured and procedural nature of ATC.[27] When this was required, it is discussed in the case analysis summary in Appendix D.

Simultaneously, the type of divergence was identified. Divergence can occur in two forms: *unknown* or *known divergence*. Unknown divergence was identified by determining whether the controller had awareness that their state awareness was consistent with the actual system state when it was not. To aid this process, common cues associated with unknown divergence were developed and used to identify instances of divergence. These domain-specific cues were developed from literature (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Silva & Hansman, 2015; Silva, 2016), to identify hazardous actions begot from poor state awareness, refined through the case study analysis process, and presented in Appendix A.

[27] These inferences are based on work discussed earlier regarding situation awareness linked to decision making and execution (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995).

Known divergence was identified by determining if the controller had awareness that their state awareness was *not* consistent with the actual system state. To help identify known divergence, common cues associated with known divergence were developed as discussed above and presented in Appendix A.

During this process the state of divergence was identified. First, the actual system state and controller state awareness were determined as described. Next, the accident or incident type was backwards propagated to provide cues to the possible final diverged state. For example, cases resulting in a LoSS, NMAC, or MAC were associated and likely result from a diverged future separation state between two aircraft, since this state measures the result. Yet the original diverged state could be different, leading the controller to incorrectly project the future separation state. For instance, the diverged future separation state may be due to a diverged future position state of one of the aircraft. In turn, this may be due to a diverged pilot's intent state, the original diverged state (e.g. case #25). This backwards propagation was accomplished using the cognitive process framework described in 4.3 Air Traffic Controller.

Re-convergence was also identified, where the controller was diverged but later aligned their state awareness with the actual system state. Re-convergence was primarily determined through controller testimony as previously described, but also facilitated by common cues presented in Appendix A.

7.3.2 Step 2 – Identify the causes of divergence

Causes of divergence were analyzed using the left-hand side of the cause and consequence framework, Figure 7-4 below, and the cognitive process framework.

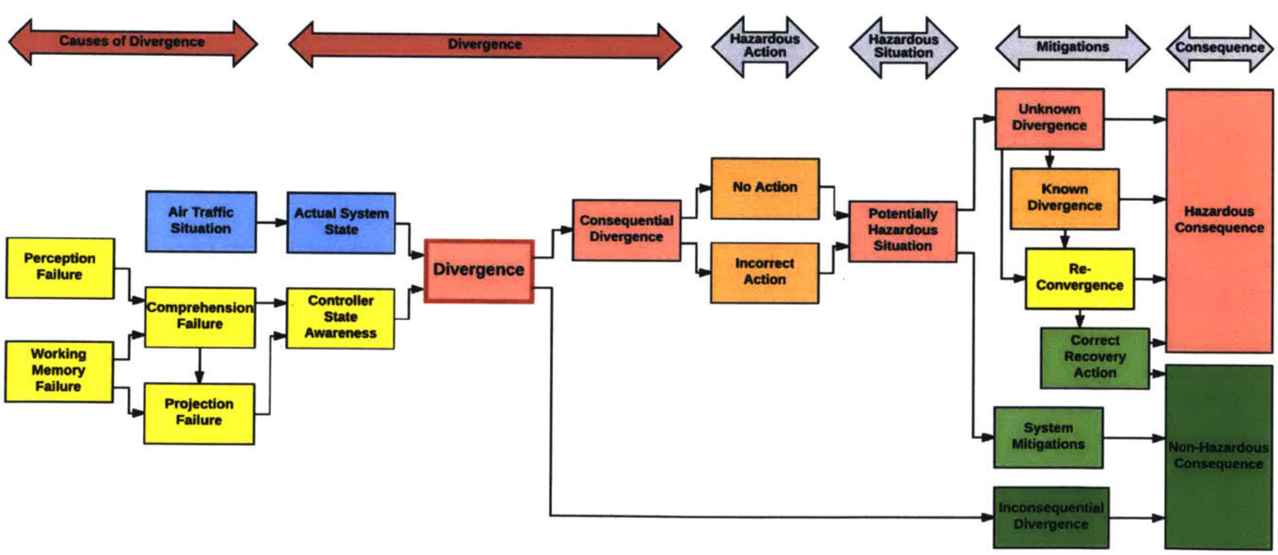

Figure 7-4. Air traffic controller divergence cause and consequence framework.

To determine divergence causes, the research began with the diverged state located in one of two areas:

1. A current state from the controller's comprehension process or working memory.
2. A future state from the controller's projection process or working memory.

Backward propagation and pattern-matching logic (Yin, 1984) were used to compare the cognitive patterns identified in the case to the cognitive process framework and cause and consequence framework to provide insight into the various paths of process failures. Using case #25 as an example, a diverged state of the future separation between two aircraft can be analyzed through backward propagation using the cognitive process framework to find the divergence a result of a lack of an observable as shown in Figure 7-5. For instance, the future separation state was found to be diverged due to a diverged pilot's intent state. The diverged pilot intent state, held in the current state assumption of working memory, occurred due to a comprehension process failure. However, the comprehension process failed in part due to a poor inference within the mental model as a result of a lack of an observation. The lack of an observation was due to a lack of perception of the observable based on the lack of an observable altogether. Therefore, one of the original sources of divergence was in the perception process from a lack of an observable of pilot intent. While pilots flying IFR must provide their intent through a flight plan, pilots flying VFR do not. Therefore, the mechanism causing a lack of an observable of pilot intent is the policy regarding VFR flight.

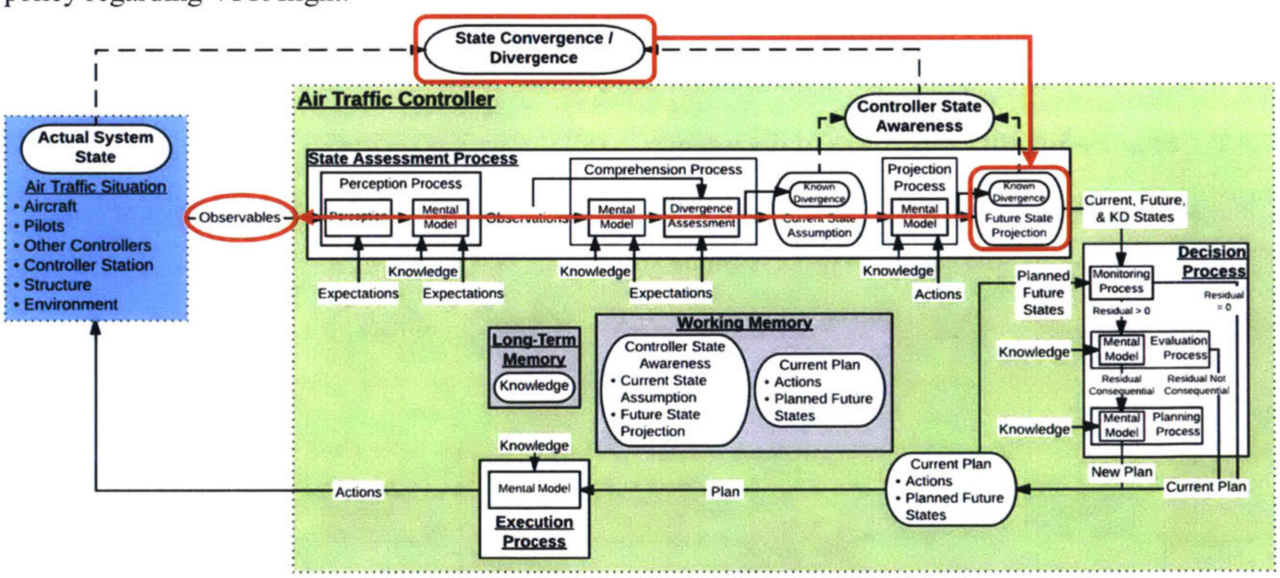

Figure 7-5. Backward propagation from divergence to its mechanism.

Therefore, the process of identifying divergence causes is to identify the original process failure leading to divergence, such as the perception process, identify the source of the process failure, such as no observable available, and identify the mechanism of the source, such as a system policy. Analysis continued until there was no evidence to identify a mechanism, source, or process failure. With aviation accidents and incidents, there is seldom a single reason for their occurrence. Therefore, evidence may support more than one process contributing to divergence and more than one source or mechanism.

Along with the framework, divergence causality questions in Appendix B helped identify divergence causes. The divergence causality questions were developed from the cognitive process framework explained in 4.3.1 State Assessment Process. At times there was no evidence of a process failure cause.

7.3.3 Step 3 – Identify the consequences of divergence

The consequences of divergence were analyzed using the right-hand side of the cause and consequence framework, presented in Figure 7-6, and the cognitive process framework. To determine divergence consequences, deductive logic, backward propagation, and pattern-matching were used (Yin, 1984).

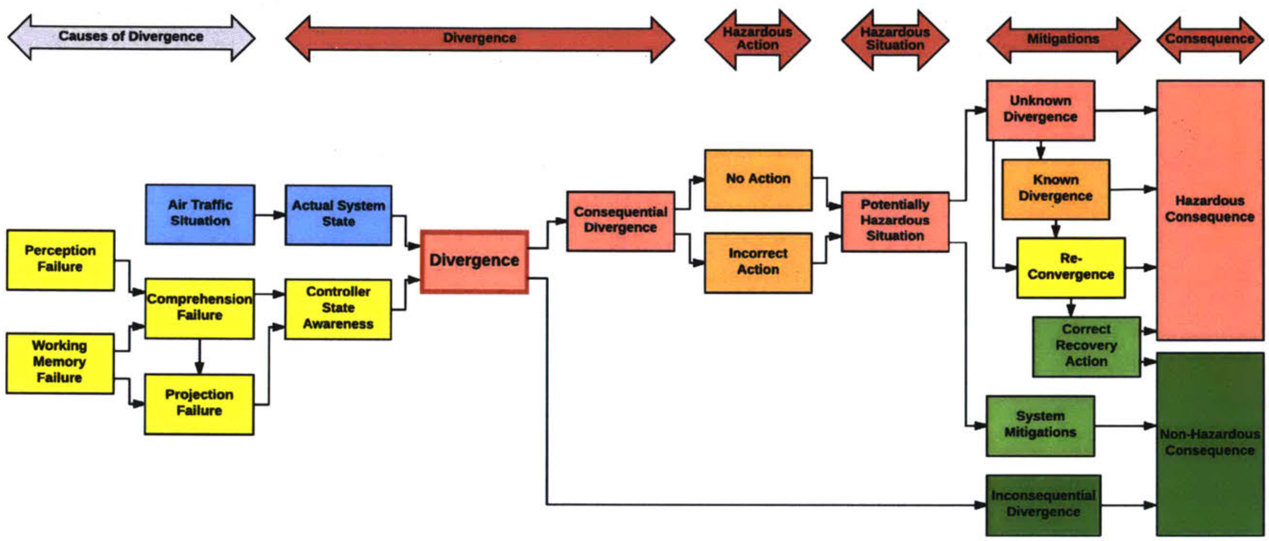

Figure 7-6. Air traffic controller divergence cause and consequence framework.

The controller's divergence was analyzed to determine the consequentiality using its definition. If the divergence was significant in a task-relevant state and consequential situation, it was consequential and led to a hazardous action and potentially hazardous situation. The nature of the dataset requires at least one instance of consequential divergence leading to an accident or incident in each case, yet there may be instances of inconsequential divergence not propagating to hazardous consequences. Also, hazardous actions propagating from divergence were identified using relevant event chronology, categorized as either "no action" or "incorrect action," and additional factors contributing to decision and execution errors were analyzed through the cognitive process framework. Some decision and execution errors were not due to divergence, but included inadequate procedural knowledge, decision violations, working memory failures, and execution slips. Hazardous actions lead to potentially hazardous situations. The potentially hazardous situation was analyzed from the hazardous actions and from backward propagation of the hazardous consequence using deductive logic. For example, with a hazardous consequence of a MAC, the potentially hazardous situation was a future LoSS. The potentially hazardous situation will propagate to a hazardous consequence unless mitigated as shown in Figure 7-6. Controller cognition post-divergence was analyzed using the cognitive process framework to identify transitions to known divergence or re-convergence. Controller state awareness and system state were determined as described in Step 1. The controller may have re-converged and provided a correct recovery action, or additional process failures may have prevented a correct recovery action. The hazardous consequence was determined from the NTSB investigation data, such as a MAC (accident) or LoSS (incident).

To ensure additional factors were considered which may have contributed to the hazardous consequence, divergence consequentiality questions were logically developed from literature, specifically using components associated with the air traffic situation described by Histon (2008), and refined throughout the case study investigation. These divergence consequentiality questions are presented in Appendix C and assisted in determining contributions to the hazardous consequence by the various agents, objects, interfaces, structure, and the environment. These additional contributing factors may involve additional instances of divergence which occurred after the initial divergence.

7.3.4 Step 4 – Identify potential mitigations

Understanding the causes and consequences of controller divergence provide insight to propose mitigations to eliminate divergence before it occurs and reduce the consequences of divergence after it occurs. To effectively and efficiently accomplish this task, mitigations should target the specific causes of divergence and the specific events or barriers following divergence leading to hazardous consequences.[28] Potential areas for mitigation are provided for each case, shown in Appendix D, and are determined using cause and consequence framework and cognitive process framework. In addition, common themes for divergence mitigations found during analysis are proposed in Chapter 8.

Mitigations for the *causes of divergence* focused on the cognitive processes of the controller, attempting to prevent the controller from becoming diverged by targeted improvements in training, the presentation of more appropriate observables, appropriate procedures to promote convergence, and through alerting and decision support systems to support convergence. Mitigations for the *consequences of divergence* focused on three areas. First, recommend procedures, structure, and architectures to transform consequential divergence to inconsequential. Second, promote controller re-convergence so they can provide correct recovery actions to mitigate. These recommendations cover similar areas as the mitigations for the causes of divergence, such as training, procedures, displays, automation, and alerting. Third, allowances for the system to mitigate the hazardous consequence regardless of controller intervention, such as appropriate procedures, technologies, structure, and architectures. In instances where

[28] Endsley and Jones argue poor SA increases the probability of undesirable performance (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Jones D. G., 1997). Targeting the causes of divergence, thus reducing the errors in state awareness, should lead to an increased probability in desirable performance.

the NTSB or other agencies recommended mitigations, comments were provided regarding additional mitigations from the cognitive process framework and cause and consequence framework compared to traditional analysis methods.

7.3.5 Case study limitations

Although data available in investigation reports were extensive, it will always be less than was available and may still fall short in providing all cues required for the study (Reason, 1990). The NTSB investigations were not focused on controller divergence; therefore, the testimony regarding the controller and other gathered data was likely neither comprehensive nor tailored to this thesis topic. Evidence of this was highlighted when it occurred. Although coding was in accordance with the air traffic controller cognitive process framework and previous human cognition literature, it was challenging at times given the investigation data was not developed for this analysis. While key words were used to code the data, expert judgment was required to account for this lack.

Reason also argued that case studies have the effect of 'digitizing' what was a complex and continuous set of 'analog' events (Reason, 1990). To mitigate this limitation, the research attempted to combine the knowledge gained from case study analysis with previous literature, the air traffic controller cognitive process framework, and the air traffic controller divergence cause and consequence framework using pattern-matching described earlier (Yin, 1984).

7.4 Example Case Study Analysis – Case #23

To illustrate the research method, an example case is presented. This case was chosen because it occurred recently, involved two commercial air carriers with significant automation and safety systems, and was an aircraft-to-aircraft conflict, the most common potentially hazardous situation.

On 15 August 2014, a radar controller's apparent unknown divergence contributed to a LoSS between a Boeing 777, American Airlines (AAL) 183, and a Boeing 747, China Airlines (CAL) 5254, while enroute near Shemya, Alaska. Both aircraft were operating on IFR flight plans and receiving separation services from the same controller in Anchorage ARTCC, sector 11R, during their night flights. AAL183 was flying west southwest bound at FL360 while Korean Airlines (KAL) 035 and CAL5254 were flying northeast bound at FL370 on a crossing route. The controller was in radio contact with both aircraft but also communicating via CPDLC to CAL5254. AAL183 requested a climb to FL370 and the controller granted the request after AAL183 passed the flight path of KAL035, creating a conflict between AAL183 and CAL5254. During the event, the controller utilized a time passing tool from the Advanced Technologies and Oceanic Procedures (ATOP) Ocean21 system to determine future lateral separation between various aircraft. The controller utilized Secondary Surveillance Radar (SSR) data via a TSD which could warn the controller of an impending LoSS via a Short Term Conflict Alert (STCA). Figure 7-7 shows a screen capture of the Ocean21 display at the approximate time of AAL183's clearance to climb to FL370 upon passing KAL035.This occurred approximately 15 minutes before the point of closest approach between the two aircraft of interest, AAL183 and CAL5254.

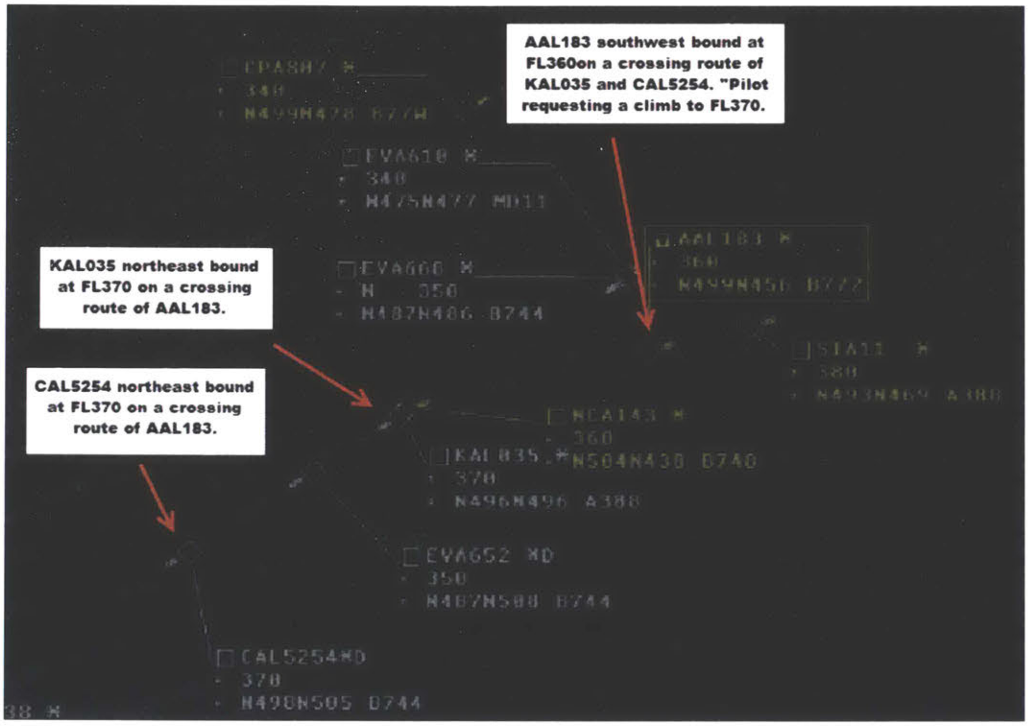

Figure 7-7. Screen capture of the Ocean21 display at the approximate time of AAL183's clearance to climb (National Transportation Safety Board, 2015).

7.4.1 Case #23 – Divergence type, divergence state, and re-convergence

Evidence of unknown divergence was based on controller testimony of inconsistent state awareness, testifying he "didn't see CAL5254 when climbing AAL183 to FL370" (National Transportation Safety Board, 2015), and his action directing an aircraft-to-aircraft conflict. In addition, his perception of the STCA activation was unexpected. There was no evidence of known divergence, but re-convergence occurred with the unanticipated STCA. The NTSB determined the controller perceived and comprehended the STCA immediately, stating that "when the conflict alert initiated, Mr. Coleman realized that he had a loss of separation. He wanted to communicate with AAL183 and descend the flight to FL360 immediately" (National Transportation Safety Board, 2015). The controller immediately took action to positively affect the situation, determining the lateral separation calculated by ATOP and attempting to contact both aircraft, albeit unsuccessfully.

The hazardous consequence (LoSS) was backwards propagated to the potentially hazardous state of an aircraft-to-aircraft conflict, the controller diverged in the future separation between CAL5254 and

AAL183. To identify the original divergence state, NTSB data suggests the controller was diverged in the future position of CAL5254. Following the climb request of AAL183, the controller utilized the ATOP time passing tool to determine the future separation between AAL183 and KAL035. The original diverged state was determined to be the existence of CAL5254. As stated earlier, the controller "didn't see" CAL5254 when climbing AAL183 to FL370. Without the knowledge of their existence, the controller was unable to project the aircraft's position.

7.4.2 Case #23 – The causes of divergence

A working memory failure likely caused the controller's divergence in the current existence of CAL5254. Three minutes before AAL183's climb request the controller communicated with CAL5254, indicating his awareness of CAL5254, yet the controller was diverged at the time of AAL183's climb request. The existence of CAL5254 was correctly comprehended and no observables were presented to change the state, indicating it faded over time due to a working memory failure. When asked why he missed CAL5254 during the climb request and subsequent clearance, the controller stated he "just missed it" (National Transportation Safety Board, 2015). No other evidence was provided to indicate the source or mechanism of the working memory failure. At the initial time of the divergence, the divergence was inconsequential. Although the controller had forgotten the existence of CAL5254, which would account for a substantial inconsistency in a task relevant state, a consequential situation had not developed.

At the moment the request was made from AAL183 to climb, the divergence became consequential due to a consequential situation developing – a request for a conflicting trajectory between CAL5254 and AAL183. Two failures of the perception process unsuccessfully mitigated the divergence. First, the controller experienced a lack of perception of CAL5254 on the Ocean21 display following the request. The NTSB stated "he [controller] looked for opposite direction traffic and saw KAL035 as a potential conflict.... but did not look past KAL035 for any other possible conflicts" (National Transportation Safety Board, 2015). Second, the controller experienced a lack of an observable of an extended conflict probe. The ATOP system included an extended conflict probe to alert controllers of impending losses of separation, but it was inhibited by the organization due to a high false-alarm rate (National Transportation Safety Board, 2015). Therefore, the combined working memory and perception failures continued the controller's unknown divergence.

7.4.3 Case #23 – The consequences of divergence

Based on the divergence regarding CAL5254, and as a rationale decision maker, the controller granted AAL183's climb request. This incorrect action was a hazardous action that led to the potentially hazardous situation of an aircraft-to-aircraft conflict between CAL5254 and AAL183.

Before a hazardous consequence occurred the controller re-converged, but failed to execute a correct recovery action for a variety of reasons. First, the STCA activated later than designed. Only 34 seconds separated the STCA from CAL5254's initial radio transmission of responding to a TCAS Resolution Advisory (RA) (National Transportation Safety Board, 2015), and only 15 seconds later they were TCAS RA complete (National Transportation Safety Board, 2015), implying the conflict had passed. STCAs are designed to provide 2 minutes warning before point of closest approach (National Transportation Safety Board, 2016), allowing the controller time to comprehend the alert, develop a plan, and execute an action to mitigate the hazardous consequence. Second, the controller utilized the ATOP automated tool to determine aircraft separation after the STCA (National Transportation Safety Board, 2015), which took valuable time. Third, both aircraft failed to reply to the controller's voice communications, likely because they were attending to a TCAS RA. Although re-converged, the controller failed to mitigate the potentially hazardous situation. However, the coordinated TCAS RAs in both aircraft provided effective system mitigations lessening the severity of the hazardous consequence to a LoSS rather than a MAC.

7.4.4 Case #23 – Potential mitigations

Insight gained from identifying divergence causes and consequences can be used to target mitigations at these two areas, and will be discussed in this context.

7.4.4.1 Potential Causal Mitigations

To mitigate the original working memory failure in general, designers should minimize the amount and length of time information is required to be stored in working memory. To address case #23 specifically, since controllers are provided with aircraft symbology continuously, this controller failed to remember CAL5254 between sampling instances. To mitigate memory lapses due to poor information sampling or attention allocation, designers should research and apply training techniques to decrease working memory critical state decay rate, which include FPS usage or rehearsal (Stein & Garland, 1993; SKYbrary, 2016). Since CAL5254 and KAL035 were flying the same route, the controller could apply 'chunking' or grouping abstractions to reduce capacity requirements for these two aircraft (Endsley, Bolte, & Jones, 2003; Histon, 2008). Finally, minimizing stress, time pressure, task load, and distraction could help mitigate working memory failures (Endsley, Bolte, & Jones, 2003).

To mitigate the lack of perception of CAL5254 upon AAL183's climb request, designers could augment transient stimuli such as CAL5254 voice radio communications with longer-lasting visual displays, such as CPDLC (Wickens, Hollands, Banbury, & Parasuraman, 2013), in addition to obvious mitigations for visual observable saliency. The lack of the extended conflict probe occurred due to high false alarm rates, in fact the Front-Line Manager (FLM) stated "if the restricted clearance was issued in a radar area and the conflict probe was not inhibited, the system would have identified the conflict and alerted the controller" (National Trasnportation Safety Board, 2012). Designers should ensure false-alarm rates are at a level to facilitate organizational use of the automation systems designed to help.

7.4.4.2 Potential Consequential Mitigations

To transform this consequential divergence to inconsequential divergence designers could require segregated altitudes for conflicting flight routes, prohibiting AAL183 to request a climb to FL370 and not allowing a consequential situation to develop. While this is structured in the NAS, controllers can override this policy workload permitting to increase efficiency, but likely at the increase of risk to controller divergence.

The STCA's ineffective timing should be researched to ensure the algorithms consistently provide timely mitigations. Also, the controller's use of the ATOP automated tool consumed valuable time needed to execute a control command for a separation maneuver. If this information was unnecessary, training or procedures should not allow this action to occur. On the other hand, if this information was necessary, designers could automate it within the STCA, including possible courses of action to reduce time delays. Finally, the controller was unaware the actions aircrews were taking to mitigate the situation. While TCAS commands are down-linked to ATC in Europe, the US has not implemented these procedures. To reduce the likelihood of late conflicting commands, policy-makers could implement these procedures or furthermore, designers could inform the controller what the aircraft is actually performing, fundamentally aiding coordination between aircrew and controllers during blind transmissions or times of increase stressors.

The system mitigated the hazardous consequence to a LoSS. Technology and procedures could be developed for aircrew to communicate a potential LoSS to controllers earlier to prevent a LoSS while still abiding by current separation responsibility structure.

7.4.4.3 NTSB and Facility Recommendations

Although the NTSB did not make recommendations for this incident, they did articulate that "If the extended conflict probe had been available at the time of the incident, it is likely that it would have detected the conflict and alerted the controller about it before he issued the incorrect clearance and that no loss of separation would have occurred" (National Transportation Safety Board, 2016). This is consistent with this research's recommendation. Additionally, the control facility conducted a system service review panel following these events and provided recommendations paraphrased below. Each recommendation from the system service review (National Transportation Safety Board Office of Aviation Safety, 2015), was highlighted by the cause and consequence framework and cognitive process framework.

1. Review options to optimize the ATOP conflict probe.
    a. Consistent with mitigations for the causes of divergence using the cognitive process framework described earlier.
2. Review the SOP regarding separation guidance and direction.
    a. Consistent with mitigations for the consequences of divergence using the divergence cause and consequence framework to transform divergence from consequential to inconsequential, described earlier.
3. Review the procedures and policies regarding altitudes within the structure.
    a. Consistent with mitigations for the consequences of divergence using the divergence cause and consequence framework to transform divergence from consequential to inconsequential, described earlier.
4. Review the operation of the CA parameters.
    a. Consistent with mitigations for the consequences of divergence using the cognitive process framework and the divergence cause and consequence framework to promote controller re-convergence and correct recovery actions, described earlier.
5. Review procedures regarding TCAS policies and parameters.
    a. Consistent with mitigations for the consequences of divergence using the cognitive process framework and the divergence cause and consequence framework to promote controller re-convergence and correct recovery actions, described earlier.
6. Review ATOP recovery training scenarios.
    a. Consistent with mitigations for the consequences of divergence using the cognitive process framework and the divergence cause and consequence framework to promote controller re-convergence and correct recovery actions, described earlier.

Although many recommendations made by this research were also made by the control facility, the original cause of divergence was not. Working memory failure and a perception failure regarding the aircraft's existence were not addressed. In addition, the cause and mitigation for the controller's failed recovery action after re-convergence was not properly addressed. The control facility recommendations address ATOP tool training, but they do not recommend understanding the information requirements or mitigations beyond training.

8 Air Traffic Control Case Study Analysis of Results

This chapter presents a case overview describing the cases analyzed, an analysis of results of divergence causes and their potential mitigations and an analysis of results of divergence consequences and their potential mitigations. The case overview provides the number of cases analyzed, potentially hazardous situations, and root diverged states to frame the study. Divergence causes are presented hierarchically, beginning with process failures, followed by a decomposition of sources and mechanisms of process failures, along with additional trends. Mitigations focus on sources and mechanisms of process failures using the cognitive process framework. Divergence consequences are presented serially, from hazardous actions to hazardous consequences. Mitigations focus on three methods: inconsequentiality, controller re-convergence and recovery actions, and system mitigations.

8.1 Accident and Incident Case Overview

Twenty-seven (27) cases were analyzed involving controller divergence as a contributing factor to an accident or incident. However, two cases involved two different potentially hazardous situations, both including an aircraft-to-aircraft and aircraft-to-terrain conflict during the same event, and therefore two different hazardous consequences, one associated with the aircraft-to-aircraft conflict and another associated with the aircraft-to-terrain conflict. Following controller re-convergence of a future loss of separation between two aircraft, the controller's recovery action was a hazardous action resulting in a vector below Minimum Vectoring Altitude (MVA). Therefore, some results are based on 29 potentially hazardous situations and 29 hazardous consequences rather than 27 cases.

8.1.1 Identified Hazardous Consequences

Each case was characterized by an accident or incident, which was associated to the hazardous consequence. The nature of the dataset leads cases to some level of hazardous consequence, yet severity levels varied. Figure 8-1 presents the hazardous consequences determined directly from NTSB investigation data. The divergence cause and consequence framework shows a potentially hazardous situation preceding a hazardous consequence. Therefore, potentially hazardous situations were grouped into common categories leading to various levels of severity of the hazardous consequence and displayed in Figure 8-1. For instance, there were 17 aircraft-to-aircraft conflicts (potentially hazardous situations) that led to 3 MACs, 7 NMACs, and 7 instances of a LoSS (hazardous consequences).[29]

[29] NMAC is defined as "an incident associated with the operation of an aircraft in which a possibility of collision occurs as a result of proximity of less than 500 feet to another aircraft, or a report is received from a pilot or a flight crew member stating that a collision hazard existed between two or more aircraft" (FAA, 2014). A LoSS refers to aircraft-to-aircraft encounters that violate FAA-mandated separation standards. Vectors below MVA (shown as < MVA on the figure) refer to aircraft-to-terrain encounters that violate FAA-mandated minimum vector altitudes.

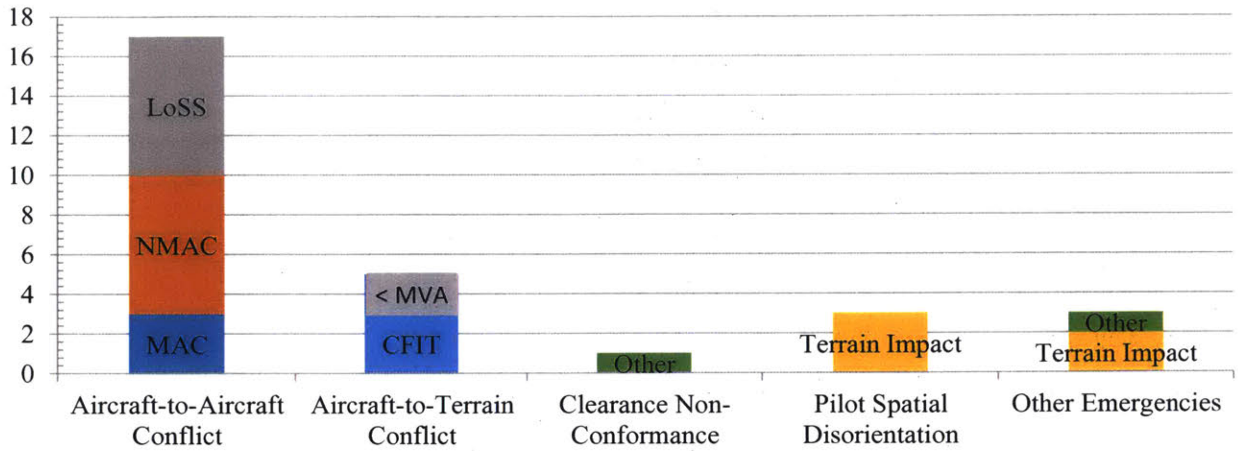

Figure 8-1. Twenty-nine (29) hazardous consequences from 29 potentially hazardous situations.

There were also 5 aircraft-to-terrain or -obstacle conflicts, resulting in 3 CFIT and 2 vectors below MVA. One (1) case of pilot clearance non-conformance resulted in a wrong airport landing. Three (3) cases of pilot spatial disorientation all resulted in loss of aircraft control and terrain impact. In 2 cases resulting in terrain impact (labeled "other emergencies"); one was due to fuel exhaustion while the other was due to engine failure. Finally, in another emergency a crewmember had a medical emergency which was delayed being handled. Potentially hazardous situations are discussed in more detail later.

8.1.2 Identified Root Diverged States

During each case the controllers became diverged in the system state, a 'root' diverged state variable was identified, which may have propagated to other diverged state variables. However, 6 cases had instances of multiple root diverged states during the accident or incident. In some cases two different controllers diverged resulting in separate root diverged states. In other cases a single controller diverged in two different root diverged states regarding the same aircraft. In others a single controller diverged in root diverged states of two separate aircraft. Overall, while there were 29 potentially hazardous situations, there were 35 independent root diverged states identified. Root diverged states and the number of divergence instances are listed in Table 8-1. The most common root diverged states were pilot intent (7), future aircraft position (6), and aircraft existence (4), which provided insight to the UAS-integration study discussed in Chapter 10. While most root diverged states were current states, all but 5 instances of divergence propagated to future state divergence, which highlights the importance of future state projection in the cognitive process framework. Nearly half (17) of the diverged states directly relate to aircraft trajectory, including the pilot intent, future aircraft position, and various future separation states. Also, 13 of the diverged states occurred due to coordination errors between human agents in the system. Each of the cases analyzed are summarized in detail in Appendix D.

Table 8-1. Root Diverged States.

Current Pilot Intent (7)	Current Supervisor's Commanded Aircraft Identity (1)
Current Aircraft Existence (4)	Current Aircraft Gyroscopic System (1)
Current MVA (2)	Current Emergency Requirements (1)
Current Pilot Spatial Orientation (2)	Current Divert Weather (1)
Current Aircraft Identity (1)	Future Aircraft Position (6)
Current Transponder (1)	Future Aircraft Separation (2)
Current Approach Runway (1)	Future Wake Turbulence Separation (1)
Current Control Responsibility (1)	Future Terrain Separation (1)
Current Coordinator's Commanded Altitude (1)	Future Aircraft Engine (1)

8.2 Identified Divergence Causes and Mitigations

Divergence causes were identified at the highest level as either a process failure of perception, comprehension, or projection, or a working memory failure of the current or future state. The reasons for the failure were identified as the failure's source, which occurred due to the source's mechanism. Yet accidents and incidents are complex and may not occur due to single causes. Some cases involved multiple potentially hazardous situations, some potentially hazardous situations involved multiple instances of divergence, and some instances of divergence had multiple contributing process or memory failures, sources, or mechanisms. Figure 8-2 shows divergence occurred due to failures in all three state assessment processes in the cases analyzed, along with working memory of the current state.[30] In total, there were 41 distinct process and memory failures of the 29 potentially hazardous situations identified.

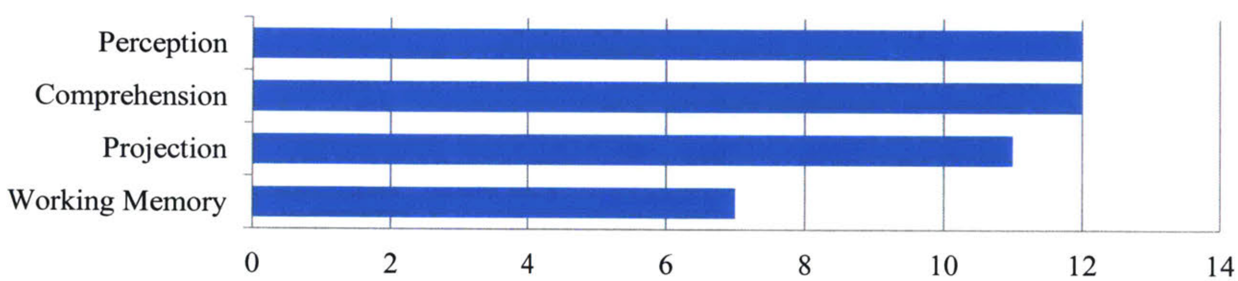

Figure 8-2. Case study distribution of process and memory failures.

The proportion of failures observed in this study differed from previous research by Jones and Endsley (1996). Their research analyzed sources of SA errors in aviation, focusing on pilots and controllers. Although SA is not a substitute of state awareness, interesting insights can be gained. Studying controllers they found that errors occurred in perception 72.4 percent, comprehension 17.2 percent, and projection 10.4 percent of the time. Their conclusions highlighted the importance of controller perception.

[30] There were no instances of a working memory failure of a future state in the cases analyzed.

These data differ from this research which found failures of perception in 26.8 percent of the instances, comprehension 29.3 percent, working memory 17.1 percent, and projection 26.8 percent, trending much less towards perception than Jones and Endsley. There may be several reasons for the differences between this study and previous research. First, the two sets of research analyzed different data sets. Second, errors coded as SA in the previous research may include factors other than state awareness, but details were not reported. Third, when multiple categories contributed to an error, they coded the error at the lowest level, e.g. perception above others. Fourth, multiple errors within the same error category were coded individually, which may bias results towards perception if perception had a higher number of sub-categories. Fifth, memory loss was coded as a perception error in their analysis. Regardless, this research would suggest comprehension, working memory, and projection may contribute to controller accidents more often than previously suspected. Mitigations toward these later state assessment processes may require greater attention.

8.2.1 Identified Perception Process Failures

Of the 11 cases of identified perception failures shown in Figure 8-2, the case study analysis identified four distinct sources of perception process failures. One case involved two sources of perception failure, leading to 12 total sources in Figure 8-3. Each source and a brief summary of the associated cases are discussed.

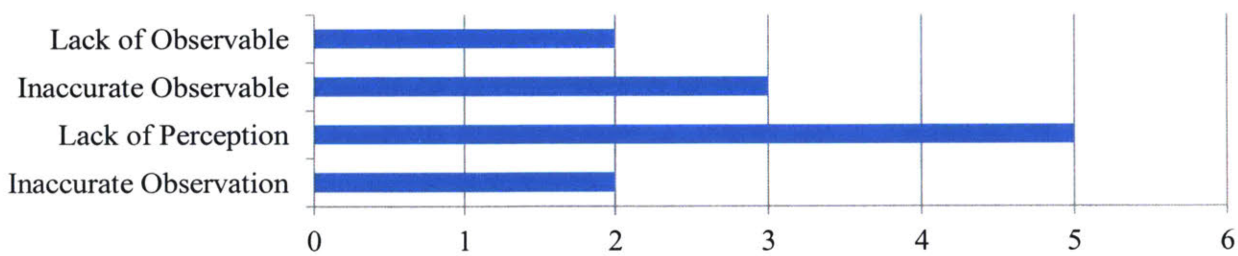

Figure 8-3. Sources of perception process failures.

8.2.1.1 Source Identified: Lack of Observable

The lack of any relevant observable (e.g. no observable) contributed to divergence in 2 cases. In case #2 a B-757 crew departed the airport without their transponder activated and did not contact departure control for approximately 8 minutes. Although the controller received the aircraft's flight progress strip, the lack of the activated transponder and voice communication (2 observables) contributed to the departure controller failing to perceive the aircraft. To mitigate, increased procedural scrutiny or automated sensing could ensure aircraft do not transition to departure control without an operating transponder, and automation could monitor primary radar returns along known flight structure to alert or tag aircraft without an active transponder. In case #25 a Cessna 150 departed VFR without a flight plan or contacting

ATC. The lack of these two observables provided an approach controller with no pilot intent, leading to an incorrect inference of intent and subsequent diverged position projection. To mitigate, FAA programs could emphasize VFR flight plans or require clearance or flight following in critical areas, but fundamental procedural changes to VFR flight, such as mandates to provide intent, would be required to ensure these observables exist.

In 2 cases, lack of observables occurred due to a system failure when the human failed to provide appropriate observables (case #2) and a system policy of VFR not requiring pilots to provide intent (case #25). The lack of observables could also occur due to system design, when the system is designed without the ability to provide an observable, such as in case #6 when the lack of an observable to provide information regarding the controller's responsibility for an aircraft that is provided in other controller software systems failed to mitigate divergence. Also, the lack of observables could occur due to system settings, when the controller sets their displays so the observable is unable to be perceived, such as in case #6 when the lack of an observable to provide MVA was de-cluttered from their display, failing to mitigate their divergence. In all, this research identified four potential mechanisms of a lack of observables. To reduce divergence potential, controllers could be presented with task-relevant states.

8.2.1.2 Source Identified: Inaccurate Observable

Inaccurate observables presented to the controller contributed to divergence in 3 cases. In case #1 a center controller failed to update an aircraft data block with their correct cleared altitude, similar to the altitude designation '↑090' shown in the data block in Figure 8-4. Another controller perceived this aircraft's inaccurate data block and directed his traffic accordingly, leading to a NMAC. To mitigate, automation could use clearances transmitted with CPDLC to automatically update data tag information without controller intervention.

Figure 8-4. Data block (HVACC, 2017).

In case #15, miscommunication between a TRACON coordinator and tower coordinator led the tower coordinator to provide an inaccurate observable of TRACON's active runway to the tower controller, leading to a LoSS. Observables besides error-prone controller voice communication are one approach to ensure constant, coordinated observables between facilities for states such as runway in use. In case #20 a pilot on a night visual approach called the wrong airport in sight to approach control, leading the controller to believe the correct airport was in sight, resulting in a wrong airport landing. Training could emphasize questioning expectations regardless of aircraft or pilot type, and controller's displays could provide conformance observables rather than only current state (Endsley, Bolte, & Jones, 2003). Overall, these cases identified all 3 inaccurate observables contributing to divergence were due to human error.

Human error can result in "a lack of an observable," an "inaccurate observable," or an "ambiguous observable" passed to the controller.[31] In fact, 11 of 27 cases involved the pilot providing no, inaccurate, or ambiguous observables, contributing to controller divergence or failing to promote re-convergence. Pilots do not always conform to clearances and in 3 cases provided no observable or an incorrect observable of their intent. Since human error may inaccurately relay intent, procedures and automation could down-link and compare aircraft automation intent to its clearance for conformance. Research toward this capability include Aircraft-Derived Data (ADD) (Courdacher & Mouillet, 2008), Mode S with Selected Altitude (SKYbrary Aviation Safety, 2017), and Center-TRACON Automation System (CTAS) (Coppenbarger, Kanning, & Salcido, 2001).

The case study analysis revealed divergence propagating from observables presented by other human agents may be a common source of observability error; the entire environment is not observable to each human agent. In Figure 8-5, a portion of the environment is observable to both pilots and controllers, for instance most voice communications. However, some of the environment is only observable to one agent. For example, pilots may be able to perceive the weather more directly than radar controllers while radar controllers may rely on observables passed from other agents. Divergence in one agent (e.g. the pilot) can propagate to divergence in another agent (e.g. the controller) through hazardous actions passed as no or inaccurate observables (communication) shown with a red arrow in Figure 8-5.

[31] Ambiguous observables are not discussed in this thesis as perception failures, but could lead to comprehension failures if they are inferred incorrectly during the association of the ambiguous observation to the state value.

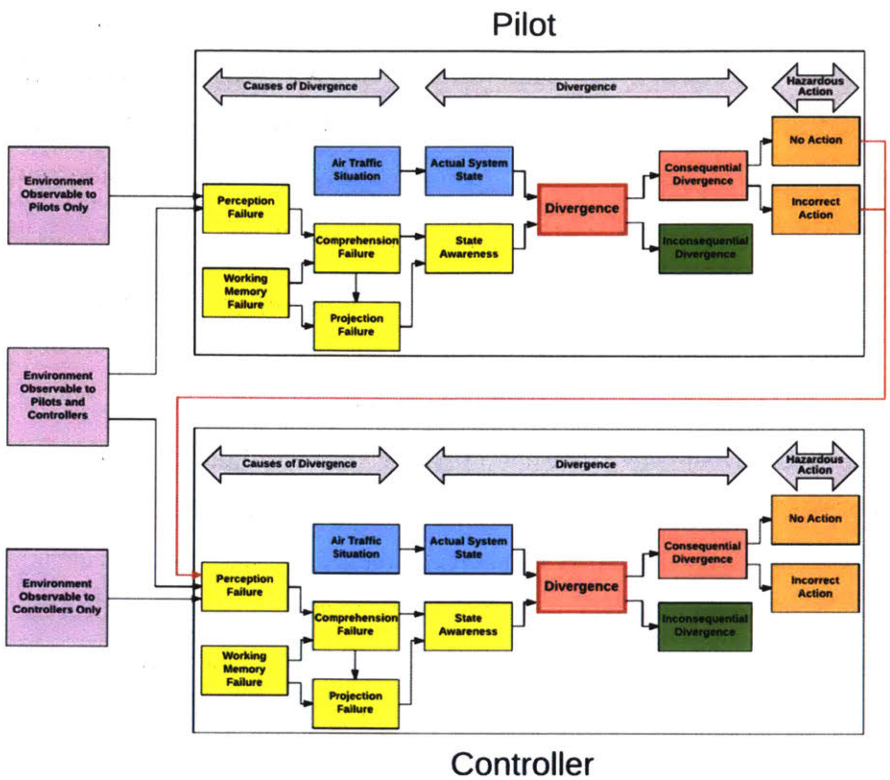

Figure 8-5. Agent observables and divergence propagation.

8.2.1.3 Source Identified: Lack of Perception

Lack of perception of an observable contributed to controller divergence in 5 cases for a variety of reasons. An indiscriminate observable led to a lack of perception in case #27 when the controller's personal display settings led to undetected flight patterns. The controller preferred a zoomed out TSD, contributing to the missed perception of irregular flight patterns when its pilot experienced spatial disorientation.

Expectation-driven scan bias contributed to a controller not attending to, and therefore not perceiving, an observable in case #12. While on approach the pilot requested to divert, yet the controller was not aware the current divert base weather was below minimums because earlier communications with the divert base led him to expect "it was probably clear." Expectation-driven attention bias also contributed to missed perceptions, as in case #2 after the crew failed to activate the transponder or communicate with departure control. Although primary radar returns were visible, the controller failed to perceive the "diamond tracking the RNAV route." Training could emphasize widening a controller's attentional focus and designers could reduce the amount of stimuli the controller is required to focus on (Wickens, Hollands, Banbury, & Parasuraman, 2013).[32] Providing integrated displays with weather information readily available and mitigations discussed earlier regarding automation tracking primary radar returns along structured routes also apply here. Finally, a tower controller in case #8 failed to perceive an aircraft on final when they cleared another for takeoff on a crossing runway due to attention allocation issues including distraction and stress. Overall, case study analysis identified the mechanisms of a lack of perception to include indiscriminate observables, expectation-driven scan and attention biases, and attention allocation issues.

8.2.1.4 Source Identified: Inaccurate Observation

Inaccurate observations contributed to controller divergence in 2 cases. In case #9 the tower controller inaccurately observed an aircraft, which took off opposite direction from its clearance. Contributing to the inaccurate observation was expectation-driven perception bias from their expected clearance conformance, an observable barrier due to airport lighting at night, and poor attention allocation. In case #11 the tower controller inaccurately observed a taxiing aircraft's readback after committing an execution slip, allowing the aircraft to taxi across the active runway when the controller meant to provide hold short instructions, due to expectation-drive perception bias and attention allocation issues from stress and high workload. Readback and hearback errors can be reduced by training to slow speech rates, emphasizing abnormal information, and minimizing the amount of information per transmission. Implementation of CPDLC in the enroute environment is also expected to reduce these errors. Case study analysis identified the mechanisms of inaccurate observations to include observable barriers, expectation-driven perception bias, and attentional allocation issues.

8.2.1.5 Identified Perception Process Failures Summary

The case study analysis identified four distinct sources of perception failures and numerous mechanisms for each source. A lack of observables or inaccurate observables can propagate from other diverged human agents to become a source of divergence in controllers, shown in Figure 8-5; however, a lack of perception was the most common source of perception failure. With accurate observables, there were 5 instances of expectation-driven biases contributing to perception failures. Expectation-driven biases occurred in 3 instances affecting the perception sub-processes and 2 instances affecting the mental model. It appears expectation-driven bias can lead to divergence in multiple ways. The sources and mechanisms refined the cognitive process framework by creating two sub-processes with two expectation inputs.

[32] More visual elements required to scan increases the likelihood critical ones will not be attended to (Wickens, Mavor, & McGee, 1997). Mitigations could reduce the amount of displayed information, reduce clutter or provide declutter options, or present fused or integrated information.

8.2.2 Identified Comprehension Process Failures

The case study analysis identified four distinct sources in the 12 cases of comprehension process failures shown in Figure 8-2, including association, inference with guessing, inference with ambiguity resolution, and integration. Many cases involved multiple sources as seen in Figure 8-6 with 16 sources for 12 comprehensions process failures. Each source and a brief summary of the associated cases are discussed.

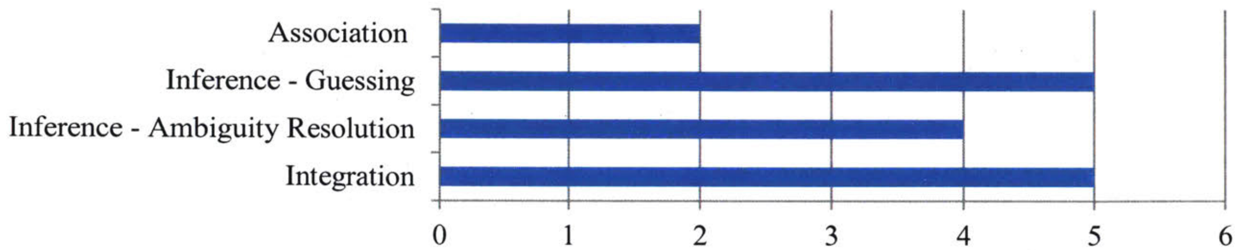

Figure 8-6. Sources of comprehension process failures.

8.2.2.1 *Source Identified: Association Failures*

Association failures contributed to controller divergence in 2 cases. In case #17, the observation of the pilot's report that he "lost his gyros" while in IMC was associated with the controller's incorrect knowledge this would only inhibit the pilot's ability to maintain heading rather than orientation to produce an inconsistent state. This led to incorrect controller actions to mitigate the situation. More detailed aircraft systems knowledge training and emphasis on information elicitation during emergencies could reduce instances of a lack of or incorrect knowledge. In case #19, expectation-driven comprehension bias overrode an unambiguous observation association to a state. The controller perceived an approach clearance readback accurately, but comprehended a different pilot intent than stated due to the expectation of pilot conformance, resulting in CFIT.

8.2.2.2 *Source Identified: Inference – Guessing Failures*

No observations propagated to inference – guessing failures in 5 cases. With no observation controllers assigned the state an inconsistent value, either a default value or expected value based on experience or projection. For instance, in case #2 the tower controller failed to confirm transponder operation of a departing aircraft, incorrectly inferring an operating transponder based on the most-likely outcome. In case #3 the tower controller pointed-out traffic for an aircraft to follow while continuing to the runway. Having no observation of pilot intent, the controller inferred the pilot would not turn to final until the traffic was in sight based on expectation-driven comprehension bias. In case #6 the tower controller had no observation of pilot intent that was being controlled on another frequency. The controller inferred his intent based on expectation-driven comprehension bias resulting in a NMAC. In case #12 the approach controller incorrectly inferred a divert airport's weather due to expectation-driven comprehension bias from projection of an earlier observation. Finally, in case #25 the approach controller incorrectly inferred the VFR pilot's intent based on expectation-driven comprehension bias from her previous experience, the most common intent of VFR aircraft departing that particular airport.

8.2.2.3 Source Identified: Inference – Ambiguity Resolution Failures

Inference failures from ambiguity resolution contributed to controller divergence in 4 cases. With ambiguous observations, controllers assigned the state an inconsistent value based on recency, conformance expectation, or reasoning. In case #1 a coordinator between two center controllers provided a command whose recipient was ambiguous. Both controllers inferred the command was intended for them, leading to divergence and a NMAC. In case #15 the supervisor told a controller to vector an aircraft whose identity was ambiguous. The controller inferred the incorrect aircraft based on one's recency of communication. In case #20 a pilot presented an inaccurate observable regarding their airport in sight, but it was ambiguous to the controller. The controller inferred incorrectly due to expectation-driven comprehension bias of pilot clearance conformance. Finally, in case #21 the controller inferred a pilot's erratic maneuvers as weather avoidance rather than spatial disorientation due to expectation-driven comprehension bias. Association and inference failures can propagate to integration failure as well.

8.2.2.4 Source Identified: Integration Failures

Integration failures contributed to controller divergence in 5 cases, propagating from association failures, inference failures, and independently due to expectation-driven comprehension bias. In case #1 the controller integrated an inaccurate observable of another aircraft's cleared altitude, his aircraft's climb rate, and an incorrect inference of an ambiguous coordinator's command for his aircraft's cleared altitude, leading to divergence and a NMAC. In case #6 the controller integrated observations of an aircraft's current altitude, the amount of time at that altitude, and incorrect inferences of another controller's plan to comprehend pilot intent. Diverged, the controller implemented a hazardous action leading to a NMAC. In case #17, along with the controller's failed association, observations of the aircraft's altitude and heading deviations and pilot communication should have led the controller to comprehend pilot spatial disorientation. In case #21 the controller failed to integrate incorrect inferences of the pilot's erratic maneuvers and missed radio calls to comprehend pilot spatial disorientation. Similarly in case #27, the controller failed to integrated perceived altitude, heading, and course deviations, missed communications, and uncommon pilot questions to comprehend pilot spatial disorientation.

8.2.2.5 *Identified Comprehension Process Failures Summary*

Inference failures were the most commons source, causing 9 of 16 comprehension failures. Designers and operators should minimize ambiguous or no observables and provide the controller unambiguous observables for task-relevant states, giving the greatest chance of consistent state awareness. Also, expectation-driven comprehension bias was a common mechanism for comprehension process failures, contributing in 8 of 12 comprehension failure cases, including expectations of clearance and SOP conformance and pilot error self-recognition. Overall, expectation-driven biases contributed in 12 of 22 perception and comprehension failure cases. Training to challenge expectations or elicit information, especially in situations with atypical, ambiguous, or no observations may reduce comprehension failures.

Another common theme identified in comprehension failures were aircraft emergencies, especially pilot spatial disorientation. All 3 cases of spatial disorientation showed a lack of recognition of pilot spatial disorientation or knowledge of aircraft systems, as well as the lack of ability to integrate observations or infer ambiguous observations relating to spatial disorientation. Training should emphasize the likelihood of receiving ambiguous or no observables from pilots during aircraft emergencies, especially spatial disorientation, and controllers should integrate observables conservatively to comprehend disorientation.

8.2.3 Identified Working Memory Failures

In the 7 cases of working memory failure shown in Figure 8-2, stress contributed to 2 cases, attention failure contributed to 1 case, and the source was unknown in 4 cases. Each source and a summary of the cases will be discussed.

8.2.3.1 *Source Identified: Attention Failures*

Attention issues contributed to working memory failure in 1 case. In case #6 the approach controller forgot he had not transferred communications and control responsibility to tower during an aircraft's approach, leading to a NMAC. Contributing to this working memory failure was an attention allocation issue as the controller had focused his attention on two other aircraft.

8.2.3.2 *Source Identified: Stress Contributions*

Stress contributed to working memory failure in 2 cases. In case #10, an approach controller vectored an aircraft to final, creating a LoSS with another aircraft. To recover, the controller vectored the aircraft below MVA forgetting the MVA had recently changed, citing stress of the situation as the reason for forgetting. In case #26 the tower controller failed to remember an aircraft's identity, swapping it with another aircraft of the same type due to stress caused by excessive workload regarding the number of aircraft in the traffic pattern. While stress cannot be eliminated in ATC, minimizing stress of time pressure (case #10) or task load (case #26) can reduce the likelihood of working memory failure.

8.2.3.3 Unidentified Source Contributions

Four other cases of working memory failure occurred for unknown reasons. In case #5 a tower controller forgot an aircraft on final and issued a takeoff clearance to a conflicting aircraft. In case #6 a controller forgot the MVA during a recovery action. In case #13 the crew requested medical assistance upon arrival, but the approach controller failed to pass this request. In case #23 the center controller forgot an aircraft he was controlling and cleared another aircraft to climb to the same altitude, leading to a LoSS.

8.2.3.4 Identified Working Memory Failures Summary

Displaying task-relevant states continuously could have assisted 4 cases of working memory failure. In 2 cases designers provided displays for the forgotten state, but the controller either did not use the display due to alleged poor display performance or decluttered the display resulting in a lack of displayed state information. In cases #6 and #10 the controllers failed to apply MVA. MVA is a display option on most TSDs, yet many controllers declutter this setting. Providing better displays would promote controller's use of MVA on TSDs, reducing the likelihood of working memory failures. In case #6, #13, and #23, controllers experienced working memory failures from states perceived through voice communications. Augmenting transient stimulus with longer-lasting visual displays may promote convergence (Wickens, Hollands, Banbury, & Parasuraman, 2013). Providing structure for controllers to 'chunk' or use grouping abstractions to associate states (e.g. control responsibility) with another observable (e.g. position) may reduce working memory failures (Endsley, Bolte, & Jones, 2003; Histon, 2008).

Following working memory failures, states transition to a variety of values. States can transition to values associated with ambiguous objects, such as the identity of one Cessna 172 (C-172) swapped with another C-172 (case #26). Values can swap with another value of the same variable, such as a wake turbulence separation swapped with another (case #4). Values could revert to a previous value, such as the previous MVA before facility changes occurred (case #10), the most common value associated with the state, such as required medical assistance (case #13), or become null or zero, such as control responsibility (case #6). Also, the value could become a 'blank state,' such as aircraft existence (case #23). Some values may represent "default values" particular states revert to upon working memory failure.

8.2.4 Identified Projection Process Failures

The case study analysis identified 2 sources of projection failures in 11instances shown in Figure 8-2. Six (6) cases were the result of incorrect knowledge passed to the mental model, while 5 were the result of mental simulation failures. Seven (7) of 17 aircraft-to-aircraft and 2 of 3 aircraft-to-terrain or -obstacle conflicts involved projection failure.

8.2.4.1 Source Identified: Incorrect Knowledge

Incorrect knowledge in the projection process contributed to controller divergence in 6 cases, 5 involving aircraft position projection. Many instances involved controllers using default values to project aircraft position, resulting in an incorrect future position and future separation state. For instance, case #3 involved a tower controller using a default value for a standard pattern turn location, while case #24 involved a tower controller using default groundspeed values for an aircraft entering the pattern to project its position. Case #7 and #22 involved tower controllers using default time delay between issuing a takeoff clearance and the aircraft beginning its takeoff roll to project future aircraft position, resulting in NMACs. In case #25 the tower controller believed an F-16 would fly a more aggressive turn than standard if told to turn 'immediately' to provide separation. To mitigate, displays could provide states required for projection that may differ from default values such as groundspeed. Also, training could emphasize type-specific aircraft performance knowledge along with appropriate levels of uncertainty. Procedures could identify boundaries for acceptable aircraft behavior as bounds for controller projection.

On the other hand, the controller in case #18 inaccurately projected zero oil pressure engine operation due to incorrect knowledge of engine degradation, leading the controller to provide vectors too far away from the runway. Developing knowledge of aircraft system degradation would aid this projection.

8.2.4.2 Source Identified: Mental Simulation Failures

Mental simulation failure contributed to projection failures in 5 cases. Cases #4 and #10 involved incorrectly projecting compression between two aircraft on final approach resulting in a LoSS. Since acceleration can be difficult for humans to perceive and project, designers could provide trend information to support mental simulation (Endsley, Bolte, & Jones, 2003), or structure to mitigate mental simulation failures through procedures considering human cognitive limitations and automation availability (Davison & Hansman Jr., 2002). For example, published airspeed points could minimize the likelihood for compression on final, as in Figure 8-7. Also, displays could present future state values directly, such as future aircraft position and separation, as in Figure 8-8.

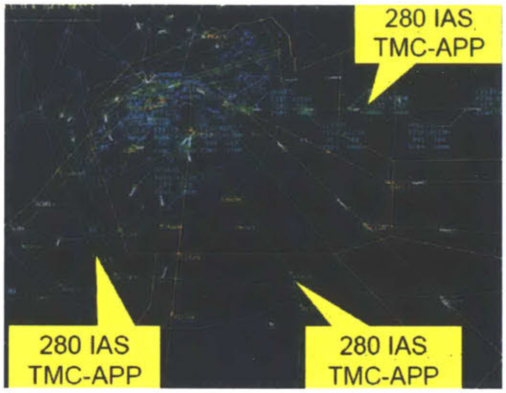

Figure 8-7. Airspeed points (Chadwick, 2013).

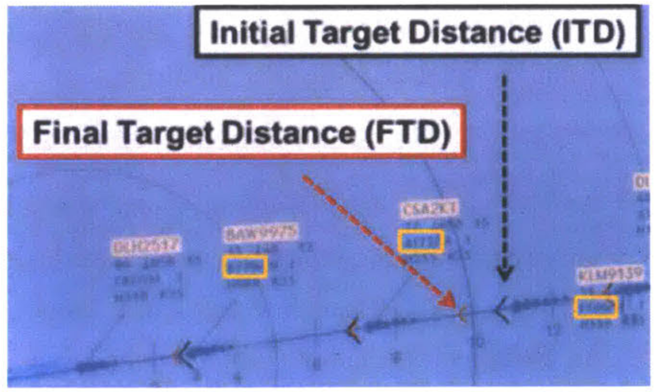

Figure 8-8. Predictive aiding (Eurocontrol, 2017).

In case #14, the controller failed to linearly extrapolate an aircraft's flight trajectory in relation to an obstacle. Automation could provide future aircraft-to-obstacle separation states and controller alerts should integrate obstacles for collision avoidance. Finally, in case #16 the departure controller provided radar vectors but failed to project the future terrain separation of an aircraft given their slow climb rate, also potentially mitigated through automation and displays.

8.2.4.3 Identified Projection Process Failures Summary

The two sources identified refined the cognitive process framework as shown in Figure 4-3. Common themes include 3 instances of incorrect knowledge involving the controller using default timing to project and 3 instances of mental simulation failure of compression on final, where controllers failed to project two aircraft decelerating. It appears controllers require aids for higher-order position projection.

8.2.5 Identified Divergence Summary

Table 8-2 presents the case study results of the causes and consequences of controller divergence. Divergence consequences are described following Table 8-2. Controller's mental model was found to be an important influence on divergence and an abstraction of the mental model within each cognitive process allowed for decomposition between disparate knowledge inputs leading to divergence. Mental models contributed to divergence in 22 of 27 cases. Expectation-driven biases were also found to be an important influence on divergence, contributing to 11 of 15 cases with perception or comprehension failures. Working memory was found to contribute to divergence in 7 cases and is often overlooked when discussing human lack of awareness with a system or environment.

Table 8-2. Case study results.

Case	Divergence Cause	Root Diverged State	Hazardous Action	Potentially Hazardous Situation	Hazardous Consequence
1	Perception	Coordinator's Commanded Altitude	Incorrect Action	Aircraft-to-Aircraft Conflict	NMAC
	Comprehension				
2	Perception	Transponder	No Action	Aircraft-to-Aircraft Conflict	LoSS
	Comprehension				
	Perception	Aircraft Existence			
3	Projection	Aircraft Position	Incorrect Action	Aircraft-to-Aircraft Conflict	NMAC
	Comprehension	Pilot Intent			
4	Projection	Wake Turbulence Separation	Incorrect Action	Aircraft-to-Aircraft Conflict	LoSS
5	Working Memory	Aircraft Existence	Incorrect Action	Aircraft-to-Aircraft Conflict	LoSS
6	Working Memory	MVA	Incorrect Action	Aircraft-to-Terrain Conflict	LoSS
	Comprehension	Pilot Intent		Aircraft-to-Aircraft Conflict	NMAC
	Working Memory	Control Responsibility	No Action		
7	Projection	Aircraft Position	Incorrect Action	Aircraft-to-Aircraft Conflict	NMAC
8	Perception	Aircraft Existence	Incorrect Action	Aircraft-to-Aircraft Conflict	NMAC
9	Perception	Pilot Intent	No Action	Aircraft-to-Aircraft Conflict	LoSS
10	Working Memory	MVA	Incorrect Action	Aircraft-to-Terrain Conflict	LoSS
	Projection	Aircraft Separation	Incorrect Action	Aircraft-to-Aircraft Conflict	LoSS
	Projection	Aircraft Separation			
11	Perception	Pilot Intent	No Action	Aircraft-to-Aircraft Conflict	NMAC
12	Perception	Divert Weather	Incorrect Action	Aircraft Fuel Exhaustion	Terrain Impact
	Comprehension				
13	Working Memory	Emergency Requirements	No Action	Passenger Medical Emergency	Delayed Medical Assistance
14	Projection	Aircraft Position	No Action	Aircraft-to-Obstacle Conflict	Obstacle Impact
15	Perception	Approach Runway	Incorrect Action	Aircraft-to-Aircraft Conflict	LoSS
	Comprehension	Supervisor's Commanded Aircraft Identity			
16	Projection	Terrain Separation	Incorrect Action	Aircraft-to-Terrain Conflict	Terrain Impact
17	Comprehension	Aircraft Gyroscopic System	Incorrect Action	Loss of Control	Terrain Impact
18	Projection	Aircraft Engine	Incorrect Action	Aircraft Engine Failure	Terrain Impact
19	Comprehension	Pilot Intent	No Action	Aircraft-to-Terrain Conflict	Terrain Impact
20	Perception	Pilot Intent	Incorrect Action	Clearance Non-Conformance	Wrong Airport Landing
	Comprehension				
21	Comprehension	Pilot Spatial Orientation	Incorrect Action	Loss of Control	Terrain Impact
22	Projection	Aircraft Position	Incorrect Action	Aircraft-to-Aircraft Conflict	NMAC
23	Working Memory	Aircraft Existence	Incorrect Action	Aircraft-to-Aircraft Conflict	LoSS
24	Projection	Aircraft Position	Incorrect Action	Aircraft-to-Aircraft Conflict	MAC
25	Perception	Pilot Intent	No Action	Aircraft-to-Aircraft Conflict	MAC
	Comprehension				
	Projection	Aircraft Position			
26	Working Memory	Aircraft Identity	Incorrect Action	Aircraft-to-Aircraft Conflict	MAC
27	Perception	Pilot Spatial Orientation	Incorrect Action	Loss of Control	Terrain Impact
	Comprehension				

8.3 Identified Divergence Consequences and Mitigations

Divergence consequences of the cases analyses are presented by discussing hazardous actions, potentially hazardous situations, controller and system mitigations, and hazardous consequences. As discussed earlier all cases resulted in consequential divergence by nature of the dataset and major changes to the NAS would be required to transform the task relevant states presented in Table 8-1 to non-task relevant states.

8.3.1 Identified Hazardous Actions

Following divergence the controller executed either no action or an incorrect action; both can be hazardous to depending on the situation. Of the 29 potentially hazardous situations, 8 hazardous actions were categorized as "No Action" while 21 were categorized as an "Incorrect Action."

8.3.1.1 Identified Hazardous Actions: No Action

For the no action cases the potentially hazardous situation must have developed on its own and the controller failed to intervene. "No action" was decomposed into instances where the controller failed to recognize the potentially hazardous situation which already existed, or recognized but forgot the potentially hazardous situation, failed to recognize their responsibility to mitigate the potentially hazardous situation, or failed to recognize the potentially hazardous situation developing. This decomposition is shown in Figure 8-9.

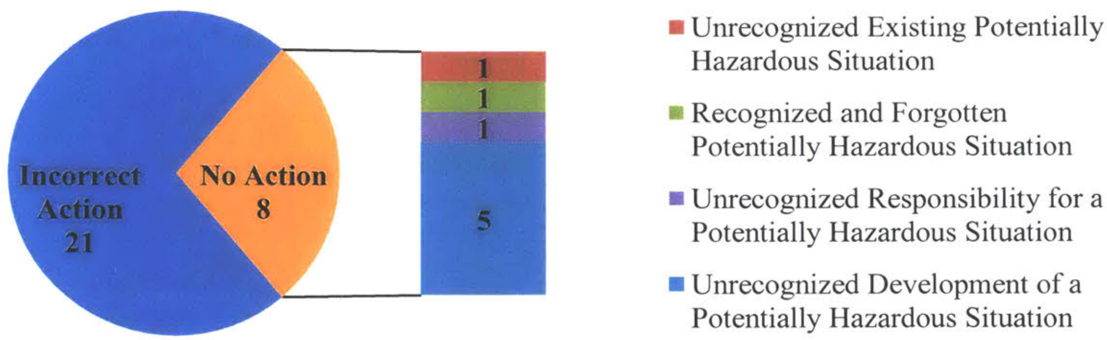

Figure 8-9. "No Action" leading to a potentially hazardous situation.

In case #14 the controller did not recognize an already existing potentially hazardous situation. The pilot contacted approach control for flight following while in conflict with an obstacle, yet the controller failed to recognize the potentially hazardous situation and act. In case #13 the approach controller forgot the medical emergency onboard, failing to pass the information on. In case #6 the controller failed to recognize his responsibility to mitigate the potentially hazardous situation, forgetting he had not transferred aircraft communication to tower. While he recognized a potentially hazardous situation developing, he believed the tower controller was responsible for both aircraft.

In 5 other cases, the controller failed to recognize the development of a potentially hazardous situation. A common example is in case #9, where the tower controller failed to recognize an aircraft taking off opposite direction from their clearance, leading to a loss of standard separation.

8.3.1.2 Identified Hazardous Actions: Incorrect Action

More often the controller executed an "Incorrect Action" which was decomposed into actions producing or failing to mitigate a potentially hazardous situation as shown in Figure 8-10.

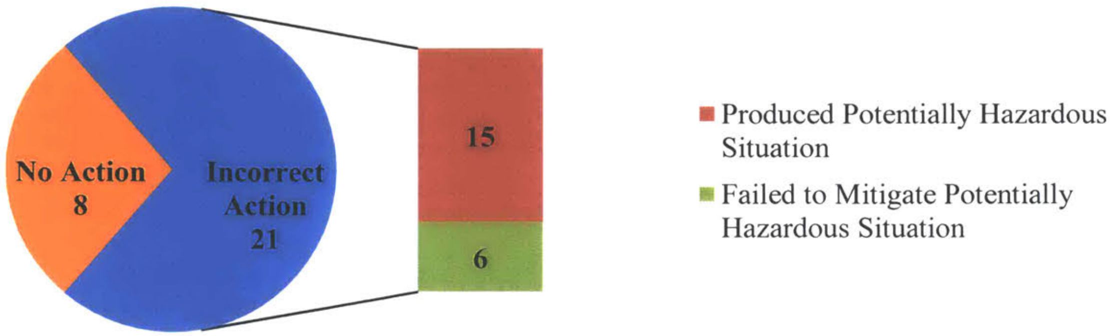

Figure 8-10. "Incorrect Actions" leading to a potentially hazardous situation.

The most common hazardous action involved 15 cases where the controller's incorrect actions produced a potentially hazardous situation. Of these, 12 involved aircraft-to-aircraft conflict and 4 of these 12 involved a tower controller providing takeoff clearance with another aircraft in conflict. For example, the tower controller in case #5 forgot an aircraft on final and cleared another for takeoff on a crossing runway resulting in a LoSS. Two (2) cases involved aircraft-to-terrain conflict. The departure controller in case #16 asked the pilot if he would like radar vectors rather than published departure routing, vectoring him below MVA, resulting in CFIT. Case #20 involved a controller providing an incorrect airport point-out, contributing to a wrong airport landing.

In the 6 other cases of incorrect actions, controllers failed to mitigate a potentially hazardous state that already existed. The most common were 5 cases involving aircraft emergencies where the controller's incorrect actions exacerbated the situation. For example, the approach controller in case #17 was diverged regarding the aircraft's gyroscopic function,[33] recommending and providing no-gyro vectors for an instrument approach rather than a VMC alternate divert, leading to loss of control and terrain impact.

8.3.1.3 Identified Hazardous Actions Summary

Divergence can propagate to multiple hazardous actions. The controller may not recognize a potentially hazardous situation exists or is developing, or the controller may recognize it, but later forget it exists or not understand they are responsible to mitigate it. The controller may produce the potentially hazardous situation with their actions or fail to mitigate it with their actions. The most common was a controller's

[33] The pilot reported he "lost his gyros," unable to maintain attitude control with his gyroscopic instrument. The controller comprehended this as a loss of heading indications not affecting the aircraft's safety in IMC. To mitigate, the controller provided 'no-gyro' vectors which are not recommended for the aircraft's state.

incorrect actions producing a potentially hazardous situation of an aircraft-to-aircraft conflict, which is consistent with ATC's primary purpose to prevent an aircraft collision, but highlights the dangers of diverged controllers. Table 8-3 presents the hazardous actions and their potentially hazardous situations.

Table 8-3. Hazardous actions and potentially hazardous situations.

Hazardous Actions	Type of Hazardous Action	Potentially Hazardous Situation
No Action (8)	Unrecognized Existing Potentially Hazardous Situation (1)	Aircraft-to-Obstacle Conflict (1)
	Recognized and Forgotten Potentially Hazardous Situation (1)	Passenger Medical Emergency (1)
	Unrecognized Responsibility for a Potentially Hazardous Situation (1)	Aircraft-to-Aircraft Conflict (1)
	Unrecognized Development of a Potentially Hazardous Situation (5)	Aircraft-to-Aircraft Conflict (4)
		Aircraft-to-Terrain Conflict (1)
Incorrect Action (21)	Produced Potentially Hazardous Situation (15)	Aircraft-to-Aircraft Conflict (12)
		Aircraft-to-Terrain Conflict (3)
	Failed to Mitigate Potentially Hazardous Situation (6)	Clearance Non-Conformance (1)
		Aircraft Fuel Exhaustion (1)
		Aircraft Engine Failure (1)
		Loss of Control (3)

8.3.2 Identified Potentially Hazardous Situations

The controller's 29 hazardous actions contributed to 29 potentially hazardous situations. The number of potentially hazardous situations in the 27 cases is shown in Table 8-4.

Table 8-4. Potentially Hazardous Situations.

Potentially Hazardous Situation	Number of Cases
Aircraft-to-Aircraft Conflict	17
Aircraft-to-Terrain or -Obstacle Conflict	5
Clearance Non-Conformance	1
Aircraft Engine Failure	1
Aircraft Fuel Exhaustion	1
Pilot Spatial Disorientation	3
Crew Medical Emergency	1
Total	29

The majority of potentially hazardous situations (17 of 29) were aircraft-to-aircraft conflicts (approximately 63 percent), followed by aircraft-to-terrain or -obstacle conflicts and pilot spatial disorientation. These situations led to hazardous consequences whose severity may have been mitigated by the controller or system, described next.

8.3.3 Identified Mitigations After Divergence

To mitigate divergence consequences, either the controller provides a correct recovery action or the system mitigates the hazardous consequence independently.

8.3.3.1 *Identified Controller Mitigations*

For the controller to mitigate the hazardous consequence, they likely need to re-converge to provide a correct recovery action. In all cases, transitions to known divergence or re-convergence occurred by perception of an additional observation, changing a state from a previous one. Some of these observations may have been previously presented observables but not perceived. Controllers perceive new observations during their normal scan pattern, by automated alerts, or controllers transition to known divergence then elicit information. Each occurs using visual or auditory senses. Table 8-5 presents the number of instances of controller transition to known divergence or re-convergence in the cases. In 9 cases the controller remained in unknown divergence. However, there were 14 instances of controllers transitioning to known divergence due to the reasons shown in Table 8-5. Also, there were 12 instances of controllers transitioning to re-convergence. Some of these instances involved controllers transitioning to known divergence then eliciting information from the system, while other instances involved controllers transitioning from unknown divergence directly to re-convergence.

Table 8-5. Instances of transitions to known divergence and re-convergence.[34]

		Transition	
		Known Divergence	**Re-Convergence**
Normal Scan	Visual	6	5
	Auditory	7	1
Alerts		1	1
Elicitation	Visual	0	3
	Aural	0	2
Total		14	12

8.3.3.1.1 Controller Alerting Effectiveness

A finding regarding the transitions to known divergence and re-convergence was the lack of alerts that transitioned the controller. Conflict alerts are often available to controllers for impending aircraft-to-aircraft and aircraft-to-terrain conflicts,[35] and are designed to re-converge a controller to mitigate the hazardous consequence. For the 17 aircraft-to-aircraft and 5 aircraft-to-terrain or -obstacle conflicts (22 total), data on alerting effectiveness was unknown in 8 encounters. Figure 8-11 shows whether alerts were available, activated, and perceived by the controller in the remaining 14 encounters.

[34] The modality for automated alerts transitioning the controller could not be determined from the investigation data.
[35] The objective of the STCA is to assist the controller in maintaining separation between aircraft by generating, in a timely manner, an alert of a potential LoSS (ICAO, 2016). The objective of the Minimum Safe Altitude Warning (MSAW) is to assist in the prevention of CFIT accidents by generating, in a timely manner, a warning of the possible infringement of minimum safe altitude (ICAO, 2016).

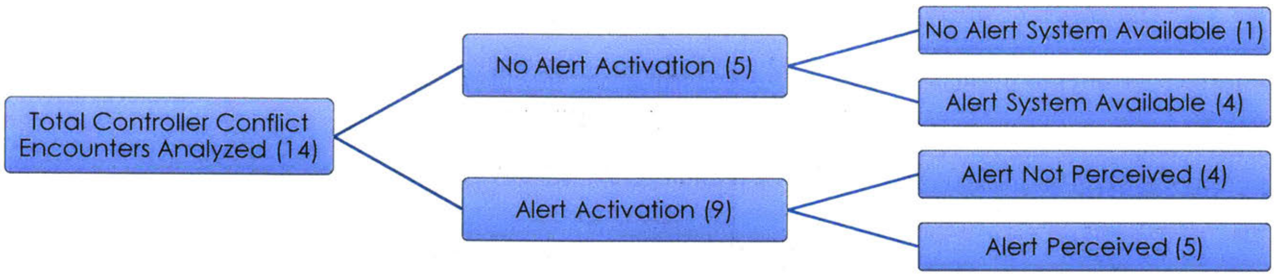

Figure 8-11. Controller conflict alert effectiveness.

Figure 8-11 shows alerting was unavailable in 1 case (#24), where the tower facility had neither radar system nor CA available. The tower controller relied on visual perception and projection for sequencing, which proved challenging due to local terrain and tree lines extending above pattern altitude, causing the aircraft to blend in with the background. Radar and alerting may have increased the opportunity for re-convergence to prevent the MAC. In 4 cases, alerting systems were available but failed to activate, including 2 NMAC and 2 LoSS, of which 3 occurred during takeoff or landing with ASDE-X alerting systems. Takeoff and landing conditions are challenging for alerting systems, but software like the "virtual intersection" to ASDE-X could provide an effective mitigation for these challenging encounters. The other case of failed activation was due to an inactive transponder, which is a current system limitation. Designers could consider robust automation alerting without aircraft participation or mandate participation with broader implementation such as ADS-B.

Four (4) of the 9 alerts that activated were not perceived by the controller, resulting in 2 MACs and 1 CFIT. Evidence from NTSB data showed these failures to perceive alerts may be due to lack of salience, attentional narrowing, and frequent false-alarms. In case #26 the tower facility had recently switched software systems (ARTS to STARS) and the controller stated "the ARTS alert was a lot sharper and louder, '... it got your attention.' However, the STARS alert was softer and did not attract attention as effectively as the ARTS alert." This lack of salience may have contributed to the controller's failed perception, contributing to a MAC. Attentional narrowing can also impact controller's perception of alerts by limiting the field of focus and preventing divided attention. In case #6 during a NMAC, the controller stated "she had not noticed a conflict alert involving the two aircraft on the radar display, although she did hear the aural alarm after they had passed." The controller had only been certified for five weeks, with busy and complex operations at the time of the incident, leading to stressors which may have narrowed her attention even more. Frequent unnecessary conflict alerts or false-alarms can lead to distrust, disuse, and disregard of true alarms, the "cry wolf" syndrome.[36] In case #19 the controller alluded to false alarms

[36] A naturalistic data study revealed 45 percent of CAs was false (Wickens, et al., 2009). In a similar study, 62 percent of CA and 91 percent of MSAW enroute, and 44 percent of CA and 61 percent of MSAW in terminal airspace are considered unnecessary (Friedman-Berg, Allendoerfer, & Pai, 2008).

stating "another controller in the area had been tracking Minimum Safe Altitude Warning (MSAW) alerts for a while. Mr. Wicks stated that nothing happened following submission of such reports, so he did not bother to turn them in." To mitigate, designers could reduce false alarm rates through specific facility programs to determine where and under what circumstances nuisance alerts occur to build and improve suppression zones (Friedman-Berg, Allendoerfer, & Pai, 2008). Including more detailed aircraft intent in the algorithm could benefit automation for separation alerting and alarms could incorporate graduations of urgency or likelihood to increase trust in automation and the potential for controller use.

Although 5 cases resulted in alarm activations and controller perception of the alerts, some alerts failed to promote re-convergence or provide sufficient time for recovery actions. The tower controller in case #9 perceived the CA, but their expectations were so strong the CA observation transformed them to known divergence rather than re-convergence. The NTSB stated, "When the CA activated on this incident, Mr. Koteff's first thought to himself was, 'is she going the right way? … Mr. Koteff said, 'my brain could not comprehend what my eyes were seeing'." The controller asked the supervisor if that "looked right" to get a second opinion. Alerts should promote re-convergence through more informatory alerting stimuli, leading to full comprehension and projection of the encounter. Also, CAs in enroute and terminal airspace are designed to alert approximately two minutes before point of closest approach (NTSB, 2016), yet in case #23 the time from first activation to the pilot's RA complete communication was 49 seconds (CA in Ocean21 system), and in case #9, the time from activation to pilot communication after point of closest approach was 21 seconds (unknown software). Although controllers did not always provide a correct recovery action after perceiving an alert, there were no MACs when the controller perceived the CA.

8.3.3.1.2 Additional Controller Mitigations

Although automation aids controller re-convergence, supervision and assists are used as redundant means of assisting in maintaining controller convergence. The majority of cases saw instructors, supervisors, and coordinators fail to help mitigate divergence for a variety of reasons, including improper staffing levels, executing administrative duties, social influence factors, non-standard communication, or divergence as well. The FAA should ensure appropriate staffing levels exist for controller tasks, create a culture allowing contrary opinions to be shared without retribution, and establish policies, procedures, and consequences regarding the use of standardized communications within a facility.

8.3.3.2 Identified System Mitigations

Without controller intervention the system is required to mitigate a hazardous consequence. Within the divergence cause and consequence framework, pilot actions may be considered system mitigations. Although pilots may not perceive the entire situation, technology has enabled them to perceive observables beyond their window view. One method of pilot (system) mitigations is through conflict or terrain alerting.

8.3.3.2.1 Pilot Alerting Effectiveness

Similar to controllers, many pilots have alerts for aircraft, terrain, or obstacle conflicts which provide decision support to mitigate hazardous consequences without controller intervention. These include both the ACAS and Terrain Awareness and Warning System (TAWS),[37] which are mandatory on certain aircraft types based on their operations, number of passengers, and weight (Federal Aviation Adminstration, 2011). Similar to controller CAs, aircraft-to-aircraft and aircraft-to-terrain and -obstacle conflicts were analyzed regarding the effectiveness of pilot alerts. Of the 22 total conflicts, 12 cases did not have enough information for analysis. Figure 8-12 illustrates the pilot alerts that were available, activated, and perceived during the remaining 10 cases of aircraft and terrain/obstacle conflicts.

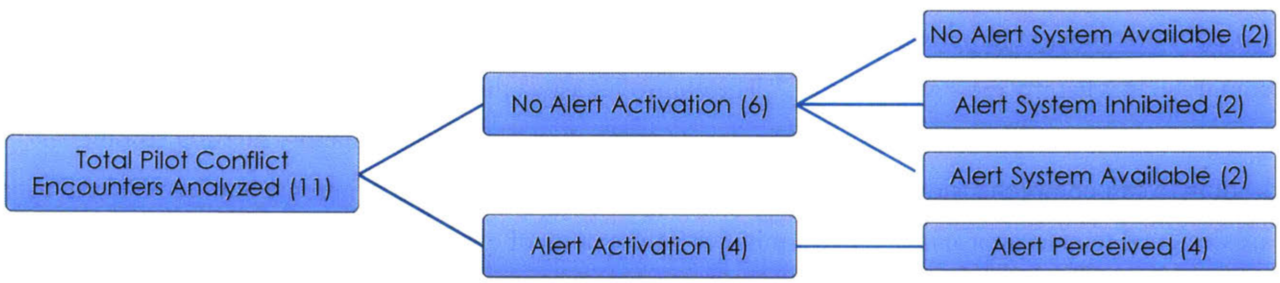

Figure 8-12. Pilot conflict alert effectiveness.

Figure 8-12 shows pilot conflict alerting was unavailable in both aircraft in two cases (#25 and #26), both resulting in MACs. In 2 other cases the aircraft were equipped with conflict alerting systems, but a component was inhibited for different reasons. In case # 24, one aircraft was equipped with an L-3 Avionics SKYWATCH Traffic Advisory System (TAS), but the aircraft was in the traffic pattern during the event and the aural alert on TAS is inhibited with the flaps at settings other than zero degrees, which also led to a MAC. In case #14, the aircraft was equipped with an Enhanced Global Proximity Warning System (EGPWS), but the pilot inhibited the system with a switch setting prior to takeoff leading to a CFIT. In the two cases with alerting systems available but no activation (cases # 2 and #7), all aircraft were equipped with TCAS but one encounter (case #2) included an aircraft with the transponder off (TCAS is not effective without transponders) and another (case #7) could have not activated due to the low altitude takeoff scenario which may have inhibited the TCAS alert automatically. In the remaining 4 cases with alert activation, 3 (case #1, #9, and #23) involved aircraft-to-aircraft conflicts where the alerts (TCAS) were perceived and may have helped mitigate the situation. However, case #16 involved a CFIT

[37] ACAS (e.g. TCAS) and TAWS (e.g. GPWS) are independent of ATC and designed to reduce the risk of MAC and CFIT respectively by providing advisories and possibly recommending maneuvers to the crew.

where the aircraft's GPS (Global Positioning System) data (unknown software) provided the pilot with awareness of a terrain conflict, but the situation had become unrecoverable and unable to be mitigated.

In summary, of the 3 MAC encounters, 2 cases involved aircraft without alerting capability and the third case involved only one equipped aircraft, but the aural alert was inhibited by a flap setting. However, all alert activations were perceived and 2 of the 3 aircraft-to-aircraft conflicts led to visual acquisition of the traffic and a subsequent avoidance maneuver.

8.3.3.2.2 Additional System Mitigations

In addition to automation, crew Visual Look Out (VLO) provides an opportunity to mitigate a potentially hazardous situation. In fact, while 23 of 29 potentially hazardous situations involved an aircraft trajectory conflict without an emergency, only 6 resulted in aircraft, terrain, or obstacle impact. Nine (9) of the 17 hazardous consequences reduced in severity were due in part or whole to crew VLO and subsequent actions while automated alerts contributed in only 2 cases. However, VLO is reduced based on many factors, one during periods of a Degraded Visual Environment (DVE). In 10 of 27 cases, DVEs contributed to the outcome by reducing the ability of pilots to perceive observables and in 1 case, the DVE affected the controller's observables. Designers should continue to develop technologies and procedures to aid onboard aircrew perception, including VLO techniques, high visibility aircraft technologies, and synthetic and enhanced vision technologies through IMC or night.

8.3.3.3 Identified Divergence Consequence Mitigations Summary

The case study analysis identified two primary methods of mitigating divergence after it occurs, which were added to the cause and consequence framework. Controllers provided correct recovery actions following re-convergence with sufficient time available. Transitions from unknown to known divergence or re-convergence occurred through their normal scan strategies or alerts, while transitions from known divergence to re-convergence occurred through elicitation. However, controller conflict alerts were found to be ineffective and only re-converged the controller in 1 instance. The importance of how known divergence changes controller actions was added to the cognitive process framework. Without controller intervention, the system mitigated divergence consequences through aircrew automated alerts and VLO.

8.3.4 Identified Hazardous Consequences

Potentially hazardous situations led to hazardous consequences baring controller and system mitigations as just discussed. Table 8-6 presents the progression from root diverged states to their potentially hazardous situations and hazardous consequences. While the root diverged states varied considerably, pilot intent appeared in multiple potentially hazardous situations and hazardous consequences, causing conflicts with aircraft, terrain, obstacles, and clearances. Common root diverged states with aircraft-to-aircraft conflicts were aircraft existence, position, and intent states. These states involve the dynamic understanding of aircraft trajectory. On the other hand, a group of states regarding aircraft operation, such as pilot spatial orientation, aircraft systems and requirements, and the environment, contributed to failed controller mitigations of a pilot's emergency situation.

Table 8-6. Root diverged states, potentially hazardous situations, and hazardous consequences.

<table>
<tr><th>Root Diverged State</th><th>Potentially Hazardous Situation</th><th>Hazardous Consequence</th></tr>
<tr><td>Current Pilot Intent</td><td rowspan="15">Aircraft-to-Aircraft Conflict</td><td rowspan="3">Mid-Air Collision</td></tr>
<tr><td>Current Aircraft Identity</td></tr>
<tr><td>Future Aircraft Position</td></tr>
<tr><td>Current Pilot Intent</td><td rowspan="5">Near Mid-Air Collision</td></tr>
<tr><td>Current Aircraft Existence</td></tr>
<tr><td>Current Control Responsibility</td></tr>
<tr><td>Current Coordinator's Commanded Altitude</td></tr>
<tr><td>Future Aircraft Position</td></tr>
<tr><td>Current Pilot Intent</td><td rowspan="8">Loss of Standard Separation</td></tr>
<tr><td>Current Aircraft Existence</td></tr>
<tr><td>Current Transponder</td></tr>
<tr><td>Current Approach Runway</td></tr>
<tr><td>Current Supervisor's Commanded Aircraft Identity</td></tr>
<tr><td>Future Aircraft Separation</td></tr>
<tr><td>Future Wake Turbulence Separation</td></tr>
<tr><td>Current MVA</td><td rowspan="4">Aircraft-to-Terrain or -Obstacle Conflict</td></tr>
<tr><td>Current Pilot Intent</td><td rowspan="7">Terrain or Obstacle Impact</td></tr>
<tr><td>Future Aircraft Position</td></tr>
<tr><td>Future Terrain Separation</td></tr>
<tr><td>Current Pilot Spatial Orientation</td><td rowspan="2">Loss of Control</td></tr>
<tr><td>Current Aircraft Gyroscopic System</td></tr>
<tr><td>Current Divert Weather</td><td>Aircraft Fuel Exhaustion</td></tr>
<tr><td>Future Aircraft Engine</td><td>Aircraft Engine Failure</td></tr>
<tr><td>Current Pilot Intent</td><td>Clearance Non-Conformance</td><td>Wrong Airport Landing</td></tr>
<tr><td>Current Emergency Requirements</td><td>Crew Medical Emergency</td><td>Delayed Medical Assistance</td></tr>
</table>

8.4 Accident and Incident Case Summary

The case study analysis revealed controller divergence causes were spread fairly evenly across perception, comprehension, projection, and working memory of the current state as shown in Figure 8-13, although no working memory failures propagated to the projection process. The distribution differs from previous research (Jones & Endsley, 1996) and may provide insight to the attention given to mitigations of later state assessment processes. No, inaccurate, or ambiguous observables contributed to perception and comprehension process failures for 31.4 percent of root diverged states. Expectations and its interaction with attention played a large role in divergence, contributing half of perception and comprehension process failures. Root diverged states varied considerably, but commons states included pilot intent, future aircraft position, and aircraft existence. Also, all but 5 instances of divergence propagated to a future state, highlighting its importance in controller divergence. Once diverged, most often controllers' executed a hazardous "incorrect action" that produced a potentially hazardous state when one did not previously exist, but they could also fail to recognize or mitigate these situations. The most common potentially hazardous situation propagating from controller divergence was aircraft-to-aircraft conflict, which corresponds to the controller's primary task of maintaining separation. Controller and system mitigations varied in their effectives to lessen the severity of hazardous consequences, with controller conflict alerts providing ineffective results for controller re-convergence and recovery actions.

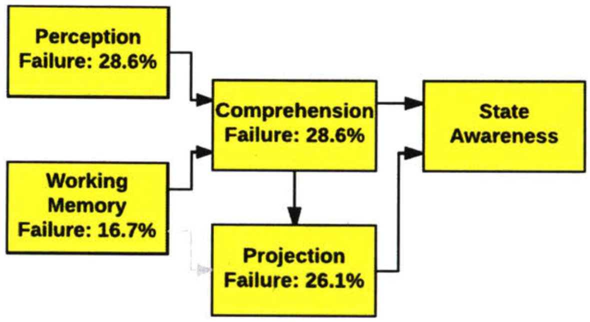

Figure 8-13. Percentage of instances of process failures.

8.4.1 Implications for Controller Divergence in the NAS

Insight gained from ATC case study analysis led to the development of approaches to mitigate divergence causes and consequences within the current NAS. These approaches address increasing the effectiveness of controller conflict alerts, training to recognize and help mitigate pilot spatial disorientation, supporting known human working memory limitations, and providing procedures and automation aids to project aircraft compression on final approach.

Controller conflict alerts were not available or not effective in the cases analyzed. Conflict alerts are designed to re-converge controllers regarding aircraft-to-aircraft or aircraft-to-terrain conflicts with enough time to execute a correct recovery action for the pilot to mitigate the hazardous consequence. Controller conflict alerts for tower facilities were unavailable or failed to activate in many cases. While ensuring conflict alert availability in tower facilities is the first step in mitigation, when alerts were available, conflict alerts (ASDE-X) failed to activate in 3 cases resulting in aircraft separation of 553, 371, and 293 feet respectively. Based on controller testimony, an approach to increase the activation threshold of these takeoff and landing cases is by implementing the ASDE-X virtual intersection protocol, which likely would have allowed conflict alerts to activate during at least 2 of these encounters. Conflict alerting algorithms may require more airport geometry specific research to enhance the ability for ASDE-X algorithms to alert during conflicts between aircraft whose runways do not physical intersect, but whose flight paths do. In the terminal and enroute environment, issues with conflict alerts appear in their effectiveness to re-converge the controller in a timely manner. Upon activation, controllers must perceive and comprehend the conflict alert, decide on a plan of action, and implement that action. However, with voice communication congestion and time requirements for correct recovery actions to take effect, late alerts may be ineffective as a mitigation for hazardous consequences. Approaches to ensure the time from alert activation to pilot maneuver is within design criteria could be investigated.

The 3 cases of pilot spatial disorientation leading to a loss of aircraft control and terrain impact highlighted the need for better training regarding the controller's ability to recognize and assist pilot spatial disorientation events. Training should provide the ability for controllers to integrate multiple observables to comprehend that a pilot is experiencing spatial disorientation, which should correspond to an emergency situation. These observables, which were apparent in all 3 cases, include heading and altitude deviations from clearance, pilot poor, ambiguous, or unexpected communication, and pilot missed communication. Training could also include the likelihood that controllers may experience expectation-driven comprehension bias (a form of confirmation bias) which would preclude controllers from comprehending pilot spatial disorientation or an emergency situation if the pilot appears to have a calm voice or fails to provide explicit, unambiguous observables of an emergency themselves. Training could also include the appropriate means to handle such situations, which likely includes vectors to VMC if available, rather than 'no-gyro' vectors. Controllers may benefit from observables providing locations of VMC versus IMC areas. Finally, controllers may benefit from procedures which recommend specific information to elicit from pilots regarding specific pilot or aircraft capabilities if flight safety is in doubt.

There were 7 cases of working memory failure leading to divergence. In 4 of these 7 cases, the forgotten task relevant states were either not available on a display, removed from a display due to clutter issues, or the controller chose not to scan the display due to its lack of perceived value. Mitigation approaches should consider designs that promote the continued display of task relevant states to reduce the burden on controller working memory. While these typically include improvements in radar displays, they could include non-dynamic displays for non-changing states such as MVA and aircraft identity. In the other 3 cases, the forgotten task relevant states were continuously displayed but forgotten during the controller's serial scan of observables, requiring task relevant states to be held in working memory between updates. Research to promote appropriate scan pattern support for the reacquisition of task relevant state awareness could reduce working memory failures and may include training, procedural, or technological solutions.

There were 3 cases of projection failures leading to divergence of aircraft separation while on approach, leading to the aircraft's compression and a LoSS. The UAS field study highlighted the challenge with mixing different levels of performance capabilities, specifically speed, especially in the tower environment. As the likelihood of these challenges increase with increased UAS integration, controllers may benefit from procedures, technologies, and training to improve their ability to accommodate this variety. Procedures designed to accommodate the merging of aircraft of various speeds into the airport environment could be developed, using specified four-dimensional approach paths compatible with UAS flight plans and navigational capabilities. Training may increase the development of mental models of these challenging approach paths which may not be developed in controllers who do not currently manage this speed variety. Automation and predictive aiding that present future aircraft position and future aircraft separation directly on the controller's display could enhance controller training. To aid automation, previously identified procedures could include mandated or recommended speed profiles integrated with aircraft automation (auto-pilot and auto-throttles) to decrease the variability of future aircraft position and likely decrease ATC automation projection error. These procedures could also be less fragile to divergence and subsequent losses of separation by providing specified procedures for controllers to execute should an aircraft-to-aircraft conflict develop, such as re-sequencing routes further away from the runway than normal missed approach procedures.

9 Current Air Traffic Control Unmanned Aircraft Systems Field Study

The planned integration of UAS operations in the NAS affords the opportunity to consider controller opportunities and divergence vulnerabilities for a CONOPS yet developed. If the causes and consequences of controller divergence are understood early in this system's development, insight gained can reduce or eliminate the causes and consequences of controller divergence to reduce or eliminate hazardous consequences.

While UAS are not fully integrated into the NAS, the US military and other public users currently operate numerous UAS types in military and civilian airspace.[38] These early examples of UAS use of the NAS were studied to provide insight towards what will or will not scope to the larger challenge of full NAS integration. To direct analysis accomplished in Chapter 10, an ATC field study of UAS-experienced controllers was conducted. From this study, consistent with UAS integration literature, a list of potential opportunities and divergence vulnerabilities areas was developed. These areas were then analyzed using the cause and consequence framework and cognitive process framework, yielding insight to system design considerations to promote controller convergence and reduce or eliminate controller divergence and divergence consequentiality within a UAS-integrated NAS, presented in Chapter 10.

9.1 Field Study Approach

To inform the future UAS-NAS integration investigation, a field study of current UAS-experienced controllers was conducted. The goal of the field study was to understand key issues in controller's cognitive processes during mixed manned and unmanned NAS operations. The study's scope involved interviewing controllers experienced managing UAS in the NAS and observing them control UAS in the NAS. To accomplish the study's goal, interview questions and observations focused on how controllers think about UAS and the strategies they use to control UAS to provide insight into their cognitive processes, specifically focusing on differences between manned and unmanned aircraft which may increase or decrease the potential for divergence. The study also focused on the current NAS structure and environment UAS operate in. This holistic view identified potential emerging divergence issues for controllers and provided insight for the selection of UAS investigation areas discussed in Chapter 10.

9.1.1 Field Study Method

Multiple qualitative methods were used to achieve the goal of the study, including a regulatory review of the operational environment, face-to-face, focused interviews of UAS-experienced controllers,

[38] According to 49 US Code 40102 public aircraft are owned and operated by the federal government, US military or state government (Gardner, 2017; Cornell Law School, 2017).

observations of controllers interacting with manned and unmanned aircraft, and phone interviews of UAS-experienced controllers. The field study used an ethnographic approach to data collection (Hollan, Hutchins, & Kirsh, 2000); essentially experts in their domain interacting with their environment were observed and questioned. To understand current UAS operations, a series of military field site visits were conducted. Before the visits, policies and procedures specific to the airport and surrounding airspace were reviewed. During the visits, participant observations and face-to-face focused interviews of UAS-experienced controllers were conducted. Following the site visits, phone interviews of UAS-experienced FAA controllers were conducted.[39]

9.1.1.1 Field Site Visit Locations

A series of site visits were conducted at nine military ATC facilities in the Southwestern US, including tower, terminal (RAPCON), and airspace or Military Radar Unit (MRU) facilities. The USAF operates five Group 4 and 5 UAS types at 12 different bases (Church, 2015), and NASA operates two Group 5 UAS types at one location (NASA, 2017). Black circles in Figure 9-1 represent the field site locations, which cover the majority of USAF and NASA UAS operation locations.[40]

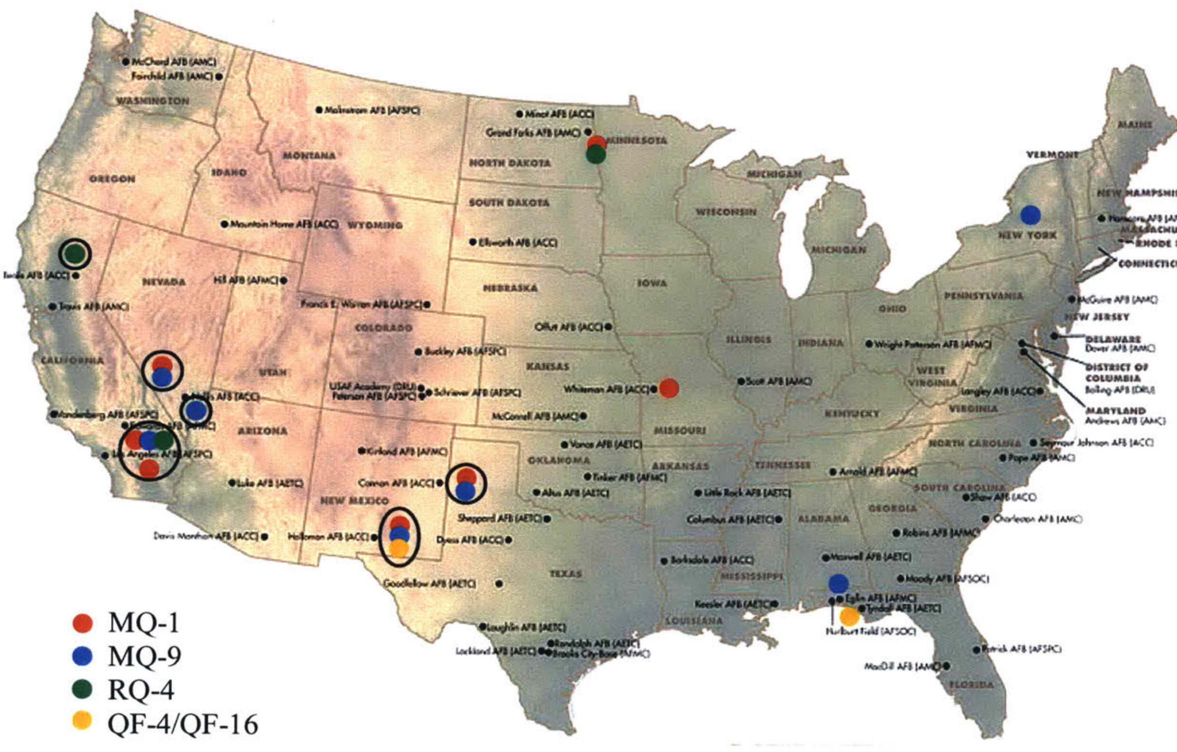

Figure 9-1. USAF CONUS UAS locations (USAF, 2017).

[39] Site visits were not conducted at FAA facilities due to lack of prior approval. However, the researcher was allowed to conduct phone interviews of one controller at a given location.
[40] The field site visit locations represented 5 of 7 MQ-1 locations, 5 of 7 MQ-9 locations, 2 of 3 RQ-4 locations, and 1 of 2 QF-4 and QF-16 locations for the USAF and NASA within the CONUS.

Site visits were conducted over a 4-week period, from 14 June 2015 to 9 July 2015. The location, dates, number of face-to-face interviews, and hours of participant observation are shown in Table 9-1. In total, 33 face-to-face interviews were conducted and 30.25 hours of observations were performed. The UA most often controlled and observed are depicted in Figure 9-2, Figure 9-3, and Figure 9-4, including the MQ-1B Predator, the MQ-9 Reaper, and the RQ-4 Global Hawk respectively.

Table 9-1. Field site visit facilities.

ATC Facility	Facility Type	Dates of Site Visits (2015)	Number of Controllers Interviewed	Employee Type	Hours of Participant Observation	Types of UAS Controlled at Facility
Cannon Tower	Tower	15–16 June	3	Active Military	3.5	MQ-1, MQ-9
Cannon RAPCON	RAPCON	15–16 June	2	Active Military	1	MQ-1, MQ-9
Holloman Tower	Tower	18–19 June	3	Active Military	3.5	MQ-1, MQ-9, QF-4, QF-16
White Sands Radar	RAPCON & Airspace	17 & 19 June	4	Active Military & DoD Civilian	2.25	MQ-1, MQ-9, QF-4, QF-16
Edwards Tower	Tower	22–23 & 29 June	4	Active Military	5.5	MQ-1, MQ-9, RQ-4
SPORT MRU	Airspace	30 June – 1 July	6	DoD Civilian	5	MQ-1, MQ-9, RQ-4
Beale Tower	Tower	25 – 26 June	5	Active Military & DoD Civilian	1.5	RQ-4
Creech Tower	Tower	6 – 7 July	3	DoD Contractor	7.5	MQ-1, MQ-9
Nellis RAPCON	RAPCON	8 July	3	Active Military & DoD Civilian	0.5	MQ-1, MQ-9, RQ-4
Total			33		30.25	

Figure 9-2. MQ-1B Predator (Defense Media Acitivity, 2015).

Figure 9-3. MQ-9 Reaper (Defense Media Activity, 2015).

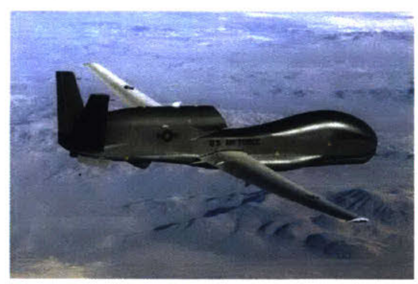

Figure 9-4. RQ-4 Global Hawk (Defense Media Activity, 2015).

9.1.1.2 Regulatory Review

Before the site visits, UAS operation and control regulations were reviewed to analyze differences in ATC procedures, restrictions, and coordination processes between manned and unmanned aircraft and between facilities. ATC guidance is hierarchical; FAA regulations supersede USAF regulations which supersede individual facility regulations. In addition, Certificates of Authorization (COAs) for each UAS were reviewed as their FAA approval to fly within the NAS. The following regulations were reviewed.[41]

[41] As of the field site visits, these regulations were the most current.

Federal Aviation Administration

- U.S. Department of Transportation – Federal Aviation Administration (U.S. DoT – FAA). (2015). Order JO 7110.65V, Change 3, Air Traffic Control.
- U.S. Department of Transportation – Federal Aviation Administration (U.S. DoT – FAA). (2014). Order JO 7210.873, Unmanned Aircraft Operations in the National Airspace System (NAS).
- Numerous Certificates Of Authorization

United States Air Force

- Air Force Instruction (AFI) 13-204, Volume 3. (2010). *Airfield Operations Procedures and Programs, Incorporating Through Change 2*, 29 June 2015.

Individual facilities

- Beale Air Force Base Instruction (BAFBI) 11-250, Incorporating Change 1. (2013). *Airfield Operations and Base Flying Procedures.*
- 27th SOG Operating Instruction 13-2011. (2014). *Remotely Piloted Aircraft (RPA) Operations.*
- Creech Air Force Base Instruction (CAFBI) 11-250. (2015). *Airfield Operations and Base Flying Procedures.*
- Edwards Air Force Base Instruction (EAFBI) 13-100, Incorporating Change 1. (2014). *Flying and Airfield Operations.*
- Holloman Air Force Base Instruction (HAFBI) 11-250. (2014). *Airfield Operations Instruction.*
- Nellis Air Force Base Instruction (NAFBI) 11-250. (2013). *Local Flying Procedures.*

9.1.1.3 Field Observations

At each site, participant observations were conducted with UAS-experienced controllers managing both manned and unmanned aircraft. Participant observation is a type of ethnography aimed at grasping a point of view from another perspective (Spradley, 1980).[42] The focus was to observe controller's actions managing UAS to identify differences in their management of manned and unmanned aircraft that may change the potential for divergence or divergence recovery through perception, comprehension, or projection of states, along with system mitigations. To accomplish participant observations, flight schedules were obtained to determine the greatest UA traffic activity and the most interaction between manned and unmanned aircraft. During periods of high traffic activity passive observations were conducted seated next to the controller with a headset, and binoculars within the tower. This afforded the ability to see the controller's displays and listen to radio communications between them, manned aircraft pilots, and UASOs. During periods of low traffic activity, contextual inquiry techniques were used to understand controller actions, local base procedures, and the operating environment. The observations were recorded with hand-written notes and pictures were taken of controller work stations for further analysis. An example of an ATCT controller's station is shown in Figure 9-5.

[42] This research encompasses a topic-oriented ethnography focused on a narrow aspect of the controller's task in a social situation. Participant observation enables the observer to focus down from descriptive observations to focused observations to selective observations, as the data presents itself in the task and environment (Spradley, 1980).

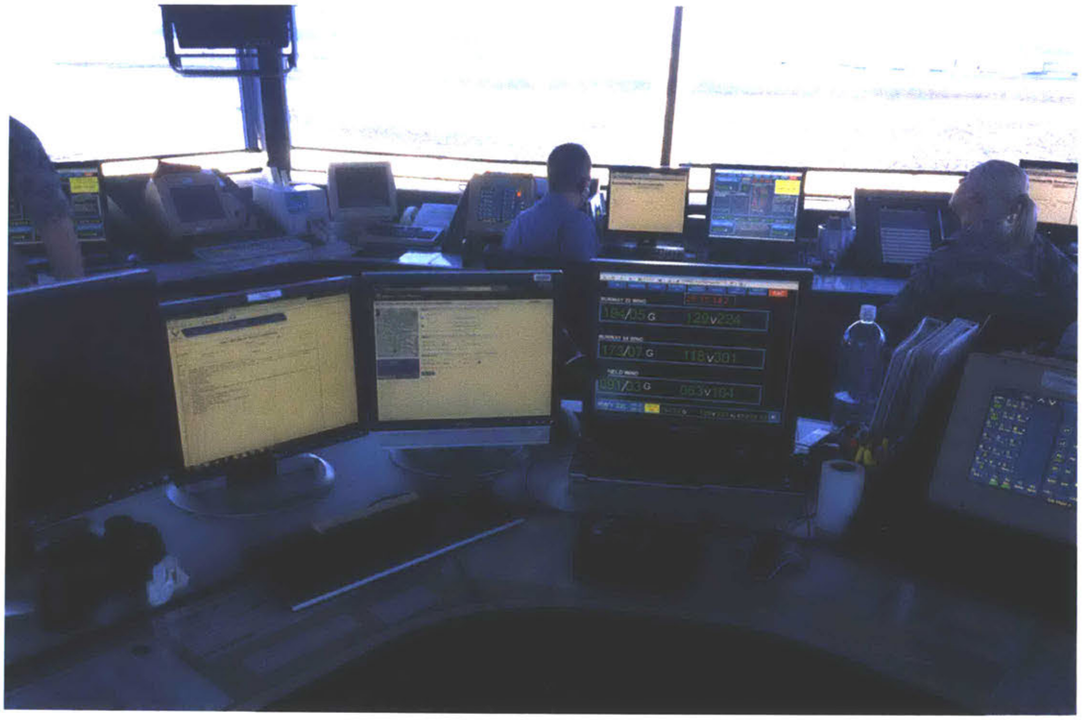

Figure 9-5. Edwards Air Force Base (AFB) control tower supervisor's station.

9.1.1.4 Focused Interviews

At each site, face-to-face focused interviews were conducted with UAS-experienced controllers. A focused, or semi-structured, interview approach was used due to its flexibility to investigate and explore the research topic and involved asking as series of structured questions, followed by probing questions to obtain additional information on interesting topic areas (Santoso, Boyles, Lawanto, & Goodridge, 2011). These probing questions gained additional understanding, clarified previous responses, elicited illustrative examples, or investigated different avenues or details.

A summary of the interview questions is in Appendix E. After demographic questions, interview questions fell within three categories: current policies and procedures for controlling UA, differences between manned and unmanned aircraft, and control strategy differences between manned and unmanned aircraft. An example from each category is shown next.

> Policies and procedures: Do you have policies for maneuvering a manned or an unmanned aircraft instead of the other to maintain separation, yes or no?
>
> Aircraft and operator differences: What differences do you think about or consider between manned and unmanned aircraft when controlling them?
>
> Control strategy differences: Do you segregate unmanned aircraft from manned aircraft more frequently than other categories or types of aircraft?

Subjects were convenience sampled; however, purposeful sampling was also used to allow deliberate selection of subjects (Maxwell, 2009). By purposefully sampling at various control facilities, this allowed comparisons of different types of control (tower, terminal, airspace, enroute), different types of employees (active-duty military, DoD civilian, DoD contractor, and FAA) and different types of UA controlled (MQ-1B, MQ-9, RQ-4, QF-4, QF-16). While many subjects met the criterion for the study (UAS experience), the controllers with the most UAS experience were contacted first via criterion sampling to gather a richer understanding of the current issues associated with controlling UA (Miles & Huberman, 1994). However, due to operational and manning requirements, at times volunteer or nominated sampling was used.

Interviews took place during controller breaks as time and the situation permitted, typically lasting 60 minutes. The interviews were conducted in a separate, quite room. Subject responses were recorded with hand-written notes and most were audio recorded.[43] Upon review, follow-up face-to-face conversations, telephone conversations, or emails were conducted to clarify responses.

Due to constraints on access, FAA facilities were not visited. However, controllers from four different FAA facilities were phone interviewed using the same methods previously described. These additional four interviews can be seen in Table 9-2, bringing the total number of focused interviews to 37.

Table 9-2. Phone interviews conducted.

ATC Facility	Facility Type	Date of Interview (2015)	Number of Controllers Interviewed	Employee Type	Types of UAS Controlled at Facility
Joshua Control	RAPCON & Center	24 July	1	FAA	MQ-1, MQ-9, RQ-4
Los Angeles Center	Center	31 July	1	FAA	MQ-1, MQ-9, RQ-4
Oakland Center	Center	7 August	1	FAA	RQ-4
Minneapolis Center	Center	7 August	1	FAA	MQ-1, MQ-9, RQ-4
Subtotal			4		
Total (face-to-face & telephone)			37		

All subjects were certified air traffic controllers or certified MRU controllers. Of the 37, 18 were tower controllers, 10 were terminal (RAPCON) controllers, 6 were airspace (MRU) controllers, and 3 were enroute (center) controllers. There were 35 males and 2 female participants, with an age range from 21 to 56 years and an average age of 37.8 years. Their ATC experience ranged from 1 year 4 months to 36 years, with an average experience of 17 years, while their experience controlling UAS ranged from 9 months to 17 years, with an average UAS experience of 5 years 10 months.

[43] Twenty (20) of the 33 face-to-face interviews were audio recorded. The other 13 interviews were not recorded due to security requirements at their respective facilities.

9.2 Field Study Results

The field study results show common themes regarding how controllers think about unmanned versus manned aircraft, how controllers manage unmanned versus manned aircraft, and the current operating environment at these facilities. The following results are a selected subset gathered during the study, yet provide insight to areas for further investigation relating to potentially increased or decreased chances of controller divergence or hazardous consequences.

9.2.1 Policies and Procedures

The ATC facility policies and procedures are derived from governing documents described previously. While FAA 7110.65V was the primary document for ATC procedures and supersedes all USAF instructions, as of 25 June 2015 there was no mention of UAS or RPA control procedures.[44] In addition, FAA 7210.873 highlights some restrictions for UAS operations, but gives little in terms of procedures for control.[45] Therefore, controller policies and procedures are developed at the USAF, and more often than not the local base level in concert with FAA COAs.

Because of policy and procedure development at the local level, UAS operations are less standardized than manned aircraft. An example of this variation can be seen in the separation criteria for UAS at the various sites. The criteria for this separation, the minimum distance allowed between aircraft, depend on a variety of factors (Federal Aviation Administration, 2014).[46] While the FAA has not differentiated UA separation criteria, current COAs and ATC SOPs prohibit the ability of visual separation criteria to be used with UA, either actively or passively, as seen in (HAFBI 11-250, 2014). This stems from the lack of onboard human perception on the UA, potentially reducing the mitigations available for aircraft conflict avoidance and placing all of the responsibility on the controller. In fact, this restriction requires positive control from ATC during unmanned operations. In addition, local base organizations have developed additional separation standards for UA as shown in Table 9-3, with additional notes added in Appendix F: VFR Separation Criteria.

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[44] FAAO 7110.65V was the current air traffic control regulation at the time the field study was conducted. Since this study, FAAO7110.65W was current as of 10 December, 2015, but continues to provide no guidance for UAS operations.

[45] FAAO 7210.873 was issued 11 July 2014 and current at the time of the field study. However, it was cancelled immediately following the completion of the study, on 11 July 2015.

[46] In general, IFR aircraft are required to be separated by 1,000 feet vertically from the surface up to and including FL410 and 3 miles (terminal) or 5 miles (enroute) horizontally (Federal Aviation Administration, 2014). For VFR aircraft in communication with ATC in the terminal area, this vertical separation requirement decreases to 500 feet (Federal Aviation Administration, 2014). VFR aircraft can also visually separate from other aircraft themselves, as long as they do not create a collision hazard or operate in a careless or reckless manner (Code of Federal Regulations, 2016).

Table 9-3. VFR separation criteria.

ATC Facility	Class Airspace	IFR		VFR	
		Vertical (feet)	Horizontal (miles)	Vertical (feet)	Horizontal (miles)
FAA-Terminal[a]	Class C	1,000	3	500[b]	target resolution[b]
FAA-Terminal[c]	Class D	1,000	3	sequencing/ advisories[d]	sequencing/ advisories[d]
FAA-Terminal[e]	Class E	1,000	3	advisories[f]	advisories[f]
Cannon AFB Tower	Class D	1,000	3	1,000[g]	3[g]
Cannon AFB RAPCON	Class E	1,000	3	1,000	3
Holloman AFB Tower	Class D	1,000	3	500[g]	3[g]
White Sands Missile Range RAPCON	Restricted	1,000	3	500	3
Beale AFB Tower	Class C	1,000[d]	3	1,000[g,h]	500 feet[g,i]
Edwards AFB Tower	Class D	sanitized[j]	sanitized[j]	sanitized[j]	sanitized[j]
SPORT Military Radar Unit	Restricted	N/A[k]	N/A[k]	2,000	5
Creech AFB Tower	Class D	N/A[l]	N/A[l]	500	No RSRS[m]
Nellis AFB RAPCON	Class A	1,000	3	N/A[n]	N/A[n]

First, UA are provided greater separation than manned aircraft. All five major sites (Cannon AFB, Holloman AFB, Beale AFB, Edwards AFB, and Creech AFB) provide greater VFR separation for UA than manned aircraft. For instance, Cannon AFB requires 1,000 feet vertical separation and 3 miles horizontal separation for UA on VFR flight plans, instead of manned aircraft's sequencing and advisory services only, equating to IFR separation criteria during VFR flight. SPORT MRU, a VFR-only control facility, provides an airspace bubble of 2,000 feet vertically and 5 miles horizontally for all UA, but only suggested sequencing and traffic advisories for manned aircraft in the airspace. Next, differences exist in separation services provided to different UA types. All five of the major sites have different separation standards for UA. For instance, Cannon AFB and Holloman AFB fly both the MQ-1 and MQ-9 and provide IFR-like separation services to VFR UA. However, Beale AFB and Edwards AFB, which fly the RQ-4, provide significant sanitization of all other aircraft during departure and recovery of their UA. Finally, differences exist in separation services provided to the same type of UA at different facilities. For instance, Cannon AFB provides 1,000 feet vertical separation during VFR operations while Holloman AFB and Creech AFB provide 500 feet vertical separation during VFR operations, all controlling MQ-1 and MQ-9. This difference is shown at RAPCON facilities as well. SPORT MRU provides separation of MQ-1 and MQ-9 aircraft of 2,000 feet vertically and 5 miles horizontally, while White Sands Missile Range (WSMR) RAPCON provides only 500 feet vertically and 3 miles horizontally.

These observations were supported by controller interviews. Controllers were asked, "Do you give unmanned aircraft additional spacing for separation services, yes or no?" Twenty-two (22) of 37 controllers responded 'yes.' Additional spacing is given based on both increased separation criteria and individual controller technique, as highlighted in both interviews and base SOPs. HAFBI 11-250 states, "RPA are unable to accept see and avoid clearances, therefore ATC must be more vigilant of separation when potential conflicts arise and shall notify all aircraft involved immediately" (HAFBI 11-250, 2014). Controllers cited numerous reasons to go above and beyond the additional separation standards provided by local SOPs, including performance characteristics of UA, lack of visual separation and see-and-avoid capability, and the increased controller workload burden should an UA execute a go-around.

9.2.2 Important Aircraft and Operator Differences

As described in 4.3 Air Traffic Controller, this research assumes controllers maintain and utilize a mental model at various levels of abstraction for their cognitive processes. To explore the differences, if any, controllers maintain in their mental model between manned and unmanned aircraft, a series of probing questions were asked. First, "Do you consciously distinguish, or keep track, if an aircraft is manned or unmanned, yes or no?" One hundred percent of the controllers responded 'yes.' Next, controllers were asked "What differences do you think about or consider between manned and unmanned aircraft when controlling them?" The controllers' initial responses are shown in Figure 9-6.

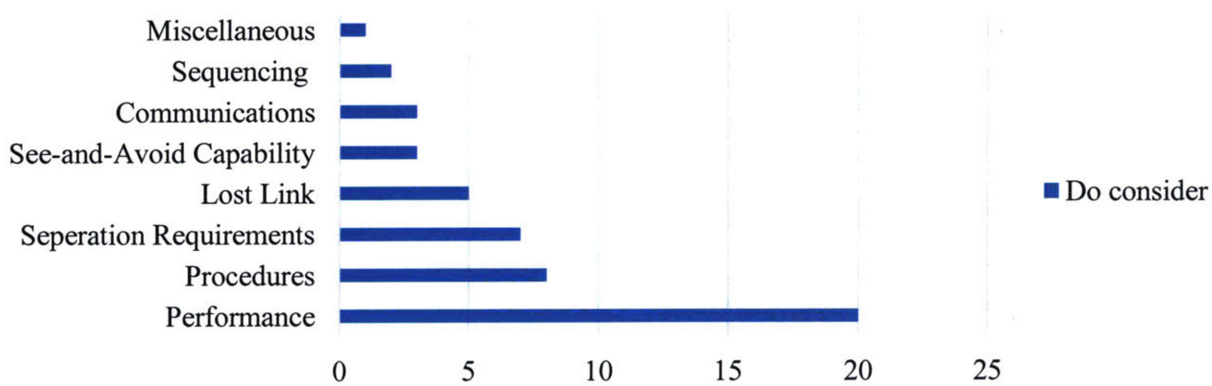

Figure 9-6. Initial responses for the differences between manned and unmanned aircraft (N=37).

After the initial responses were recorded, specific follow-up questions were asked if a category was not cited. For example, if the controller did not cite a difference in "speed of response" between manned and unmanned aircraft, the following question was explicitly asked: "Do you consider differences in the speed of response between manned and unmanned aircraft, yes or no?" Up to 9 follow-up categories were queried and their responses are represented in Figure 9-7. Each bar represents the number of controllers who "do consider" differences in this category between manned and unmanned aircraft.

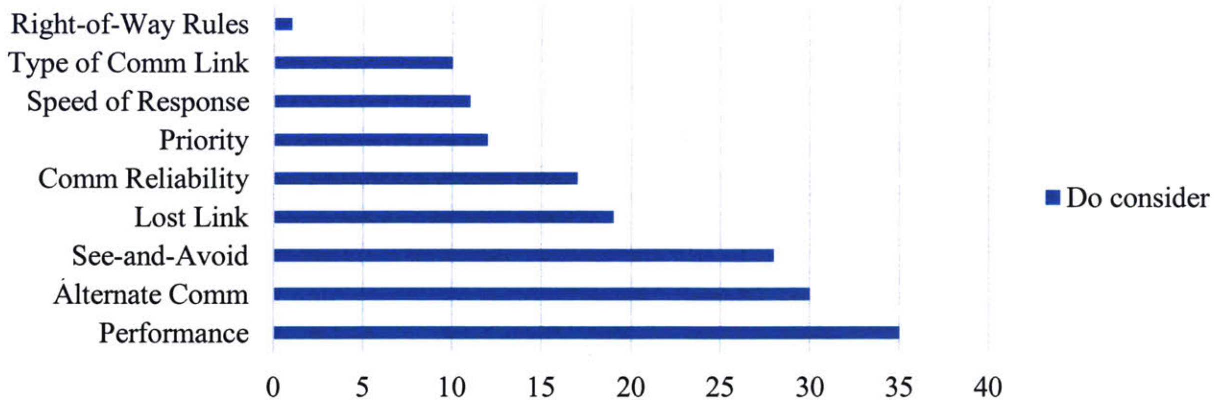

Figure 9-7. Follow-up responses for the differences between manned and unmanned aircraft (N=37).

9.2.2.1 UAS Flight Characteristics

The field study revealed UAS differences in performance and flight operations compared to manned aircraft. These will be investigated in Chapter 10 as UAS flight characteristics. First, as seen in Figure 9-6 and Figure 9-7, performance differences were considered by the largest number of controllers. To explore performance differences further, controllers were asked to "Rank these categories from most important to least important to consider between manned and unmanned aircraft," with the categories of climb rate, descent rate, aircraft velocity, turn performance, and loiter capability. The results shown in Figure 9-8 reveal that aircraft velocity differences were ranked most important, followed by climb rate and turn performance.[47] In all cases, controllers correlated UA with comparatively lower velocities. Participant observations revealed similar results, with one controller stating, "To us, it's just another airplane. It's that simple, it's just another airplane, except he's [UAS] slow."[48]

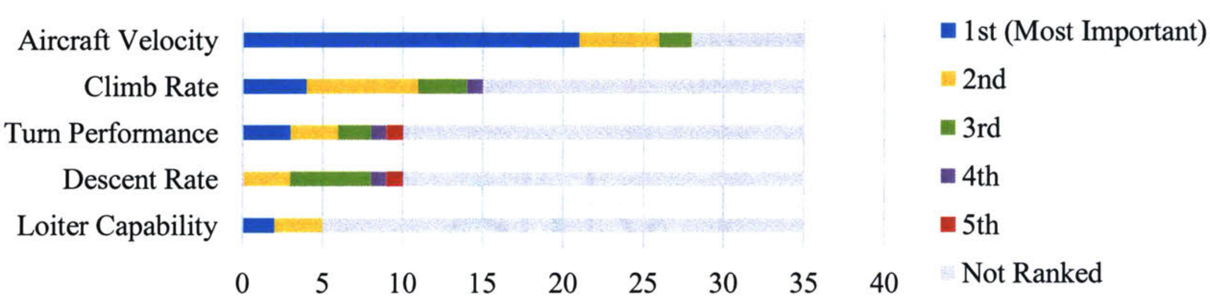

Figure 9-8. Ranked performance differences between manned and unmanned aircraft (N=35).[49]

[47] Statistical analysis showed velocity as (statistically significant) the most important factor compared to others, seen by the Friedman Test with a $Q = 31.67$, $p < 0.001$ and the Wilcoxon Signed-Ranks Test with a $T = 3.915$, $p < 0.001$.
[48] Cannon AFB tower controllers quote during participant observation, 15 June 2015.
[49] $N = 35$. Here, two controllers failed to rank the categories of performance differences. In fact, as seen in the figure, few controllers were able to rank all five categories.

Similarly to performance characteristics, controllers were asked "Do you find that you are able to anticipate actions of unmanned aircraft more reliably, less reliably, or the same compared to manned aircraft?" Although Figure 9-9 shows approximately 62 percent say 'more reliably,' the responses appear to vary depending on the controller's type of facility. Of the 18 tower controllers interviewed, 15 responded 'more reliably' while 3 responded 'the same.' However, of the 3 center controllers 1 responded 'the same' while 2 responded 'less reliably.' Tower controllers cited the reasons for better anticipation or projection of UA position were due to exact and more specified procedures, more route structure and restrictions, and lower airspeeds. However, a center controller stated "UAS are doing a mission that requires more movement,"[50] while another stated "manned aircraft fly from point A to point B, while unmanned aircraft want to loiter as long as they can."[51] These flight profiles, such as loitering in enroute airspace and static, long-duration flights may present controller projection challenges of future UA position in an UAS-integrated NAS, possibly leading to divergence.

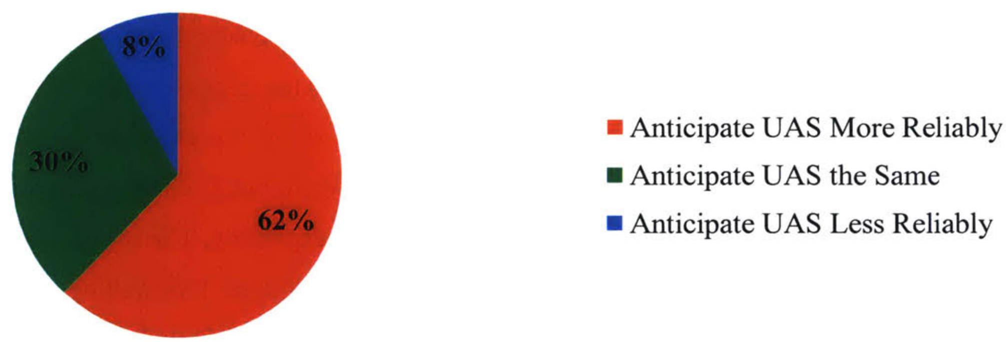

Figure 9-9. Anticipation of unmanned aircraft compared to manned aircraft.

9.2.2.2 Lost Link

Figure 9-7 shows that 30 of 37 controllers considered alternate communications as a manned and unmanned aircraft difference; the second-most cited response. Although many controllers said alternate communication (such as a land telephone line) is only used during Lost Link (LL) or radio failure, some discussed its advantages during normal operations to better facilitate complex instructions. Regardless, alternate communications were considered a benefit to better understand UASO intent.

Just over half (19 of 37 controllers) responded they consider LL as an UA difference. In the event of LL, controllers require knowledge of LL state and the aircraft's intent following LL. Although LL alternate communication procedures are in place,[52] communicating LL status can be delayed. Although many

[50] Center controller, interview 31 July 2015.
[51] Center controller, interview 7 August 2015.
[52] Typical UAS COAs require an alternate communication means inside the NAS. Usually this consists of a land-line telephone so the UASO and controller can communicate during No Radio (NORDO) or lost link.

locations have local SOPs, errors and intent uncertainty still occurs. A Creech AFB tower controller stated, "We had an MQ-1 go lost link with other aircraft in the pattern. The aircraft turned the wrong direction and started climbing. The PIC tried to call but at that point, ATC was talking with three other aircraft. It ended up being a HATR [Hazardous Air Traffic Report]."[53] A change in runway direction without a commensurate change to the LL procedure contributed to the HATR. In addition, LL procedures can change real-time due to compounding emergencies onboard the UA. Some controllers must monitor the transponder beacon code to perceive either a LL squawk or emergency squawk.[54] Lost link represents a significant area of controller divergence vulnerability investigated in Chapter 10.

9.2.2.3 Lack of Onboard Human Perception

Figure 9-7 shows see-and-avoid, the result of the lack of onboard human visual perception, as the third-most cited difference between manned and unmanned aircraft. Due to UAS limitations of visual separation and visual clearances, controllers change their strategies to compensate. For instance, a tower controller discussed the challenges of UAS perception capabilities stating, "We could fix and handle the speed [differences] if they could accept visual separation and follow [other aircraft]. But instead, we must give them separation, call their base turn, etc. It is more workload for the controller."[55] The lack of onboard human perception is an area of divergence vulnerability investigated in Chapter 10.

9.2.3 Scenario-Based Questions

To further understand how UAS affects controllers' decisions and strategies, a series of scenario-based questions were asked regarding conflict resolution. The controllers were asked to "imagine a scenario where a manned aircraft and unmanned aircraft are approaching. Who would you contact first to issue a command to maneuver?" Notional aircraft encounter geometry is in Figure 9-10.

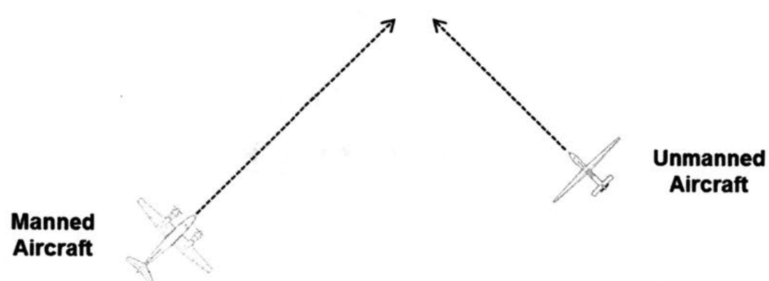

Figure 9-10. Manned and unmanned aircraft approaching.

The question was parsed between two different urgencies, a non-urgent scenario where the aircraft were approaching and the controller must maneuver the aircraft to *maintain standard separation*, and an urgent

[53] Creech AFB tower controller during participant observation, 6 July 2015.
[54] Creech AFB tower controller during face-to-face interview, 6 July 2015.
[55] Cannon AFB tower controller during participant observation, 15 June 2015.

scenario where the aircraft were in conflict and the controller must maneuver the aircraft to *avoid a collision*. The question was also decomposed so each aircraft was operating under either IFR or VFR, leading to four combinations of flight rules between the two aircraft. Figure 9-11 displays the results of which aircraft the controllers chose to maneuver during non-urgent scenarios, as an aggregate of all four IFR and VFR combinations, while Figure 9-12 shows the aggregate of the urgent scenarios. Controllers chose the manned aircraft more frequently in all cases, but as a conflict scenario becomes more urgent controllers tended to choose the manned aircraft even more frequently. While 63 percent of controllers chose the manned aircraft in the non-urgent cases, 80 percent chose them in the urgent case.

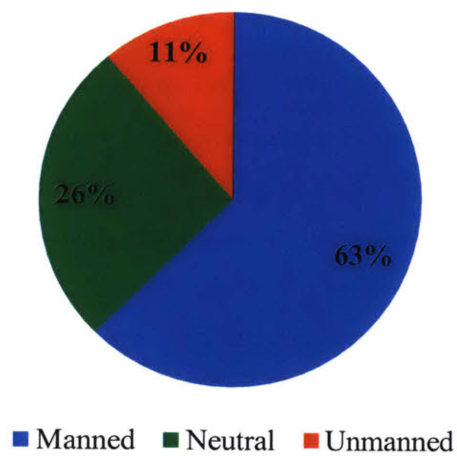

Figure 9-11. Controller choice of who to maneuver, aggregate non-urgent case (N = 80).

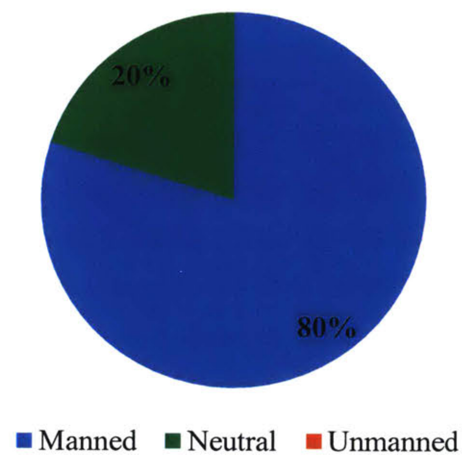

Figure 9-12. Controller's choice of who to maneuver, aggregate urgent case (N = 80)

Next, controllers were asked if seven factors contributed to their decision on whom to maneuver. Figure 9-13 shows how many controllers believed the category was a factor in their decision, with the black bars corresponding to a non-urgent situation and the gold bars corresponding to an urgent situation.

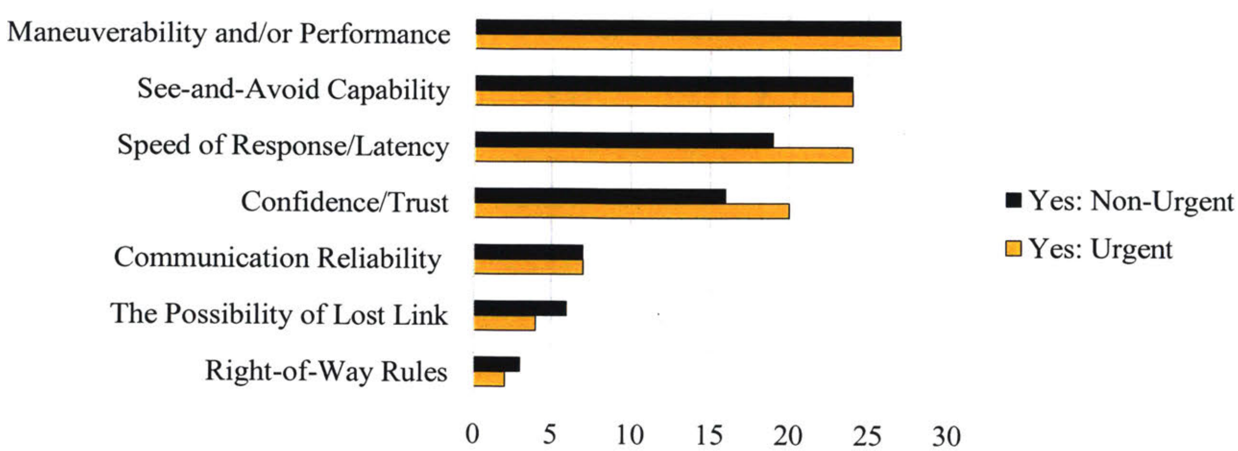

Figure 9-13. Factors influencing a controller's decision on who to maneuver.

As Figure 9-13 shows the most significant factors in the controller's decision remained fairly consistent between urgent and non-urgent cases. Aircraft maneuverability and performance remained the most often cited factor and appears to be a large difference between manned and unmanned aircraft. Next, see-and-avoid capability differences appear to affect which aircraft to maneuver. Speed of response or latency of response was the third-most cited factor in their decision, with more controllers citing it as a factor as situation urgency increases, as 19 controllers cited this during non-urgent scenarios while 24 cited it during urgent scenarios.[56] Further analysis indicated a possible difference between types of UA the controller typically managed. For instance, 14 of 19 controllers with RQ-4s at their location considered speed of response a factor in their decision on who to maneuver during non-urgent scenarios. However, only 5 of 18 controllers experienced with MQ-1 and MQ-9 considered speed of response. During urgent scenarios the trend continued with 16 of 19 RQ-4 controllers considering speed of response but only 8 of 18 MQ-1/MQ-9 controllers. One explanation may derive from differences in the level of control automation between RQ-4s and MQ-1s or MQ-9s.

Controllers were asked, "Do you have different control strategies for unmanned aircraft compared to manned aircraft, yes or no?" Over two-thirds of the subjects (27 of 37) replied 'yes.' Based on field observations and interviews, it appears different control strategies were again used for different UA types. MQ-1 Predator and MQ-9 Reaper are flown via stick and throttle, with a lower level of automation compared to the RQ-4 Global Hawk, which is flown via a keyboard and mouse. With the RQ-4, operators are inputting higher-level state commands such as route of flight, while MQ-1 and MQ-9 operators can provide pitch and bank angle commands directly. It appears these differences lead to different control strategies and techniques for controllers. A Beale AFB tower controller stated, "They [RQ-4] have a clear inability to adjust" when referring to the flexibility of the RQ-4.[57] Another controller stated, "When they [RQ-4] start, everything else stops."[58] This lack of flexibility has led controllers to be more apt to use procedural control, where the departure and recovery procedures are explicitly defined and approved in whole then seldom changed. On the other hand, a Cannon AFB tower controller stated, "The RPAs [MQ-1 and MQ-9] get held more often," referring to the controllers providing real-time changes to their clearance for separation adjustments.[59] Here, controllers use positive control with MQ-1s and MQ-9s, providing explicit heading and altitude commands, even when the aircraft are operating VFR. In fact, an Edwards AFB tower controller (who had managed both types of UA) stated he considered differences among UAS based on control architecture, specifically noted the differences between "a stick and throttle

[56] Exact binomial test, McNemar test p-value = 0.0588.
[57] Beale AFB tower controller, interview on 25 June 2015.
[58] Beale AFB tower controller, interview on 25 June 2015.
[59] Cannon AFB tower controller, interview on 15 June 2015.

versus keyboard control,"[60] going on to say the difference in control architecture affected both his trust in an aircraft and his perceived workload. Various control automation and architectures appear to be a difference considered by controllers and may present a divergence vulnerability in the future, which is discussed in Chapter 10.

[60] Edwards AFB tower controller, interview on 29 June 2015.

10 Implications for Future Unmanned Aircraft Systems-National Airspace System Integration

Differences between manned and unmanned aircraft may increase the likelihood of controller divergence; however, there may also be opportunities for controllers to remain converged more often or re-converge more quickly. Responses from the ATC UAS field study directed areas of investigation as discussed in Chapter 9. These four areas were investigated to identify both controller opportunities and divergence vulnerabilities and include the lack of onboard human perception, lost link, UAS flight characteristics, and various levels of control automation. All four areas are consistent with UAS-integration literature (GAO, 2005; FAA, 2012; Federal Aviation Administration, 2013; Kenny, 2013; Comstock Jr., McAdaragh, Ghatas, Burdette, & Trujillo, 2014; Yuan & Histon, 2014; Rabe, Abel, & Hansman, 2016). While not comprehensive, this list of areas appears important for NAS development considerations and will demonstrate the utility of the divergence cause and consequence framework and the cognitive process framework. Each will be presented with controller opportunities and divergence vulnerabilities along with potential mitigations.

10.1 Lack of Onboard Human Perception

10.1.1 Divergence Vulnerabilities from Lack of Onboard Human Perception

Controllers who do not have direct perception of the environment (only tower controllers directly perceive the environment) are vulnerable to divergence regarding important factors in their environment which may not be perceived by them. Surveillance systems these controllers rely upon may not detect factors such as non-cooperative aircraft or significant weather conditions. The lack of these observables may lead to a controller perception failure under the cognitive process framework. Observables not presented by displays can propagate from a perception failure to a lack of awareness of these important factors in the environment. If the controller is unaware of aircraft or significant weather that may be in conflict with an aircraft they are controlling, this could result in consequential divergence and the controller could execute a hazardous action. Because of this potential for controller divergence regarding an aircraft-to-aircraft conflict or significant weather penetration, which exists for both manned and unmanned aircraft, manned aircraft pilots using their onboard perception provide a potential mitigation.[61] Pilots may perceive aircraft and weather the controller cannot directly perceive. The pilots can provide aircraft and significant weather observables to the controller to prevent controller divergence,[62] maneuver

[61] During VMC federal regulations require all pilots to maintain their own separation by "see and avoid" (Code of Federal Regulations, 2016).
[62] In-flight turbulence and icing awareness is largely gained through Pilot Reports (PIREPs) (Armanini, Polak, Gautrey, Lucas, & Whidborne, 2016; AeroTech Research Incorporated, 2017). FAA 7110.65W states controllers

to avoid the other aircraft or significant weather and mitigate the hazardous consequence themselves, or provide these observables to the controller to re-converge the controller.

For example, a radar controller may not be aware of an aircraft because it is non-cooperative or outside of radar coverage and the controller's sensors do not detect and display it to the controller.[63] If this aircraft's flight path is in conflict with another aircraft's flight path the controller is responsible for, the controller's divergence may be consequential. The controller may fail to provide a vector mitigating the potentially hazardous situation of an aircraft-to-aircraft conflict, or unknowingly provide a vector that produces an aircraft-to-aircraft conflict. Another example of this type of controller divergence vulnerability is significant weather, such as icing and turbulence. Currently, many weather sensors and displays that provide controllers observables of significant weather lack detail, timeliness, and accuracy (Federal Aviation Administration, 2015), leading to a lack of controller awareness of significant weather in the environment. If an aircraft's flight path is in conflict with significant weather, the controller's divergence may be consequential. The controller may fail to provide a vector mitigating the potentially hazardous situation of significant weather penetration, or unknowingly provide a vector that produces a significant weather penetration. However, manned aircraft pilots may perceive non-cooperative traffic in their flight path or airframe icing and inflight turbulence the controller's sensors may not have detected, allowing them to present observables to re-converge the controller or mitigate hazardous consequences themselves.

With UAS in the NAS, this controller divergence vulnerability from unperceived factors in the environment, such as aircraft or weather, is more likely to be consequential because the UASO cannot provide observables to re-converge the controller (aid controller mitigations post divergence) or take action to mitigate the hazardous consequence themselves due to the lack of an onboard pilot to perceive these hazards (provide system mitigations post divergence). As illustrated in Figure 8-5, the lack of onboard human perception likely increases the UASO's divergence vulnerability regarding important environmental factors which may require direct perception. For example, UASOs do not have "out of the window" visual perception and therefore may lack traffic or airframe icing observables for perception, propagating to UASO divergence regarding these factors. Also, UASOs lack vestibular and proprioceptive observables to perceive turbulence, propagating to UASO divergence regarding weather factors. If the UA's flight path is in conflict with an unperceived aircraft or significant weather such as icing or turbulence, the UASO's divergence could be consequential, possibly resulting in failed mitigations of the potentially hazardous situation. Therefore, the lack of UAS mitigation increases the risk

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should solicit PIREPs when requested or when one of numerous conditions exists or is forecast for their area of jurisdiction, see FAA 7110.65W (Federal Aviation Administration, 2015).

[63] Non-cooperative aircraft are defined as aircraft without an active transponder (Lacher, Maroney, & Zeitlin, 2007).

of hazardous consequences of midair collisions, loss of control, or structural failure. Divergence vulnerabilities due to a lack of onboard human perception are illustrated by the framework in Figure 10-1.

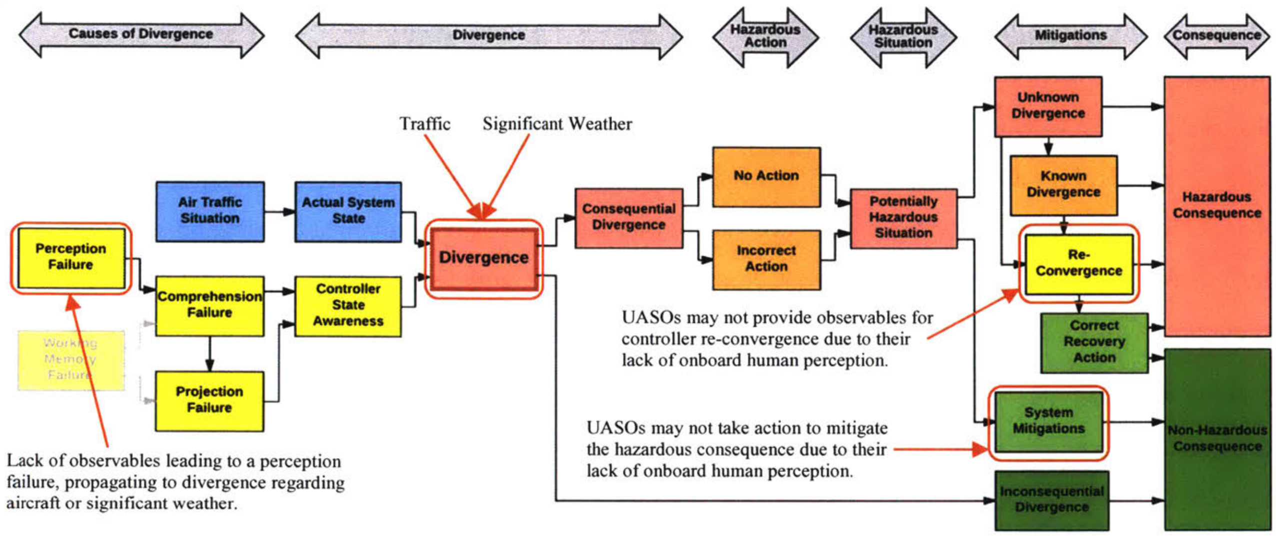

Figure 10-1. Vulnerabilities due to a lack of onboard human perception.

10.1.2 Potential Mitigations for the Lack of Onboard Human Perception

One approach to mitigate the causes of controller divergence from a lack of perception is to increase the observables controllers receive, such as aircraft and significant weather information. To accomplish this, increased sensor capability may detect consequential aircraft, such as non-cooperative aircraft, and significant weather, along with reducing false return issues which may increase controller use of primary radar returns. The FAA could mandate cooperative equipment on aircraft throughout the NAS or corporations could produce less expensive alternatives for transponder or ADS-B equipment to provide aircraft observables to the controller. In addition, more accurate and greater coverage radar capabilities could afford increased aircraft and significant weather observables. With increased UAS sensors to detect other aircraft and significant weather, described later, architecture could provide these observables from UAS sensor systems to the controllers for their benefit.

Mitigating hazardous consequences after controller divergence can be accomplished by transforming the divergence from consequential to inconsequential. This could occur by transferring separation responsibility from the controller to the UASO, which is currently accomplished with manned aircraft and will be discussed later. This could mitigate risk by transferring responsibility to agents better aware of hazards in the environment, although this would likely require technology and procedures for UASOs to remain well clear of conflicts. This transforms some aircraft separation from a task-relevant to a non-task-relevant state, rendering the controller's divergence inconsequential. Also, UAS could be segregated from other aircraft and significant weather by regulation or procedure, rendering divergence inconsequential by not allowing a consequential situation to develop.

Another approach to mitigate hazardous consequences is to promote controller re-convergence so controllers can provide a correct recovery action. This may require the controller to perceive additional observables such as weather and non-cooperative air traffic as discussed earlier, including enhanced sensors and displays to provide for re-convergence through observables and alerts. Alerts typically provide the final opportunity for re-convergence before a hazardous consequence occurs and should be designed with graduations of urgency to reduce distrust, disuse, and disregard. Alerts should also be fully integrated with UAS including unique UAS characteristics discussed in sections 10.2, 10.3, and 10.4.

Another approach to mitigate hazardous consequences is for the system to provide mitigation from hazardous consequences stemming from controller divergence, which can be accomplished by the UASO. However, the UASO may also be unaware of important factors in their environment as described earlier. To mitigate the causes of UASO divergence due to a lack of observables stemming from a lack of onboard human perception, UASOs should be able to perceive observables that are consequential in the environment. Traditional collision avoidance systems for intruder sensing (e.g. TCAS) provide cooperative traffic observables, and the FAA is considering ACAS requirements for UAS operations (FAA, 2017). However, ACAS provides collision avoidance guidance as a last resort rather than to remain well clear and the lack of onboard human perception requires the ability to perceive non-cooperative aircraft observables. Equivalent Visual Operations (EVO) is a NextGen concept using technology, such as Sense-And-Avoid (SAA) or Detect-Sense-and-Avoid (DSA),[64] to replace visual lookout and provide these non-cooperative observables to reduce UASO divergence due to perception failures from a lack of observables (FAA, 2017), providing mitigations to remain well clear and avoid collisions. Also, airframe icing and inflight turbulence sensors could provide objective measurements of icing conditions and turbulence severity observables to reduce UASO divergence due to perception failures from lack of observables. With these additional observables, UASOs could remain converged with consequential aircraft and significant weather allowing them to plan and execute correct actions to prevent potentially hazardous situations, such as aircraft-to-aircraft conflict and significant weather penetration, or mitigate hazardous consequences, such as midair collisions and structural failure. Because of potential high levels of control automation on UAS, automating avoidance maneuvers could be considered due to UASO performance limitations and the potential for lost link. However, automating maneuvers away from ATC clearances requires robust automation nearly free of false alarms.

[64] For a review, see *Sense and Avoid in UAS: Research and Applications* (Angelov, 2012).

Overall, while the lack of onboard human perception may not change the magnitude or state of controller divergence, it could transform controller divergence from inconsequential to consequential because of the lack of UAS mitigation capability. Instead of non-hazardous consequences due to manned aircraft awareness and actions, potentially hazardous situations such as aircraft-to-aircraft or aircraft-to-weather conflict may more easily transition to hazardous consequences of aircraft collision or significant weather penetration without UAS onboard human perception.

10.2 Lost Link

10.2.1 Controller Divergence Vulnerabilities from Lost Link

The field study in Chapter 1 also revealed lost link as an area of concern. Controllers who do not have direct perception of UAS lost link status or lost link intent are vulnerable to perception failures due to difficulties understanding link status and likely vehicle actions in the event of lost link. This perception failure vulnerability could lead to divergence regarding important factors relevant to aircraft position projection. A change in the status of the UAS control link to lost link means the UASO can no longer change the trajectory of the aircraft; therefore, the controller cannot command a change to the aircraft either. However, this state may be unobservable to the controller. Also, when lost link occurs it may change an unmanned aircraft's intent from its current clearance without providing the controller an observable of the unmanned aircraft's new intent. These two states, lost link status and lost link intent, may be used by the controller to project the unmanned aircraft's future position, propagating to a lack of awareness of the unmanned aircraft's future position. If the controller is diverged in the unmanned aircraft's future position and the unmanned aircraft is in conflict with another aircraft, this could result in consequential divergence and the controller could execute a hazardous action. For example, a controller may not be aware of an unmanned aircraft's lost link because of a lack of observables regarding lost link. If the unmanned aircraft's lost link intent changes from its current clearance and places the unmanned aircraft in conflict with another aircraft's flight path, the controller may fail to accurately project the unmanned aircraft's future position. The controller's divergence may be consequential and the controller may fail to provide a vector mitigating the potentially hazardous situation of an aircraft-to-aircraft conflict. In addition, UASOs may be unable to provide observables to re-converge the controller post divergence due to communication challenges. Also, UASOs cannot take control actions to provide direct mitigations for hazardous consequences themselves due to lost link. Divergence vulnerabilities due to lost link are illustrated by the framework in Figure 10-2.

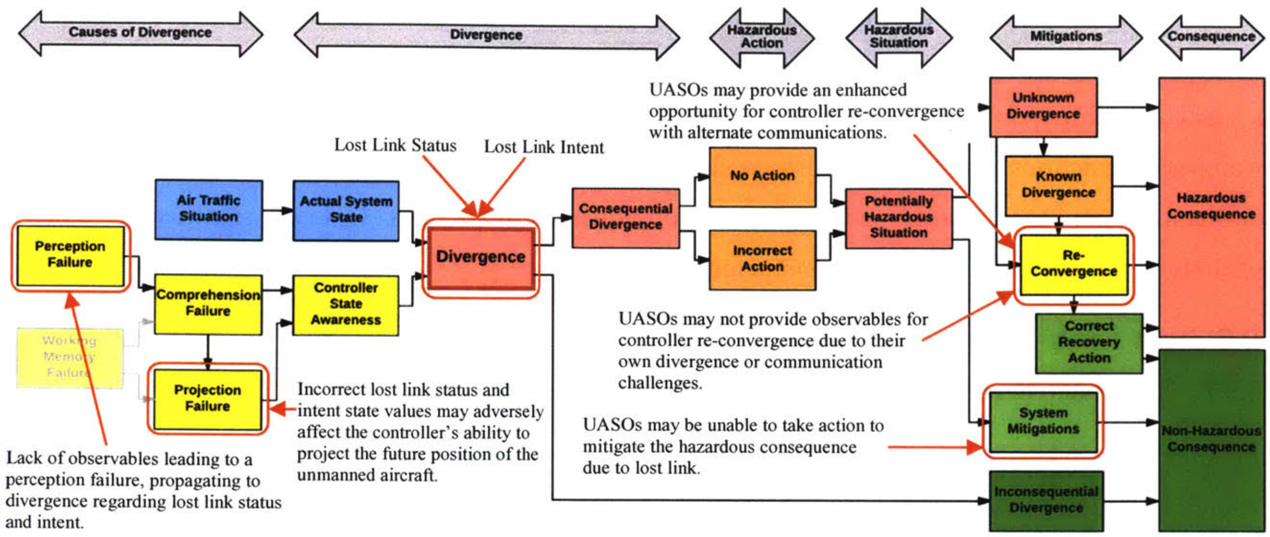

Figure 10-2. Vulnerabilities due to lost link.

10.2.2 Current UAS Procedures for Lost Link

Procedures observed during the ATC UAS field study provide some observables to controllers for lost link status and intent information. The most common methods of providing lost link observables were UASO communications providing both lost link status and intent, a discrete transponder beacon code (e.g. 7400) providing lost link status, and SOPs through the COA process or local regulations providing lost link intent. However, these current methods each have potential divergence vulnerabilities as well.

UASO communications provide the controller observables regarding lost link status and intent, but as illustrated in Figure 8-5 the controller may still be vulnerable to divergence regarding these important factors due to perception failures in two different ways. First, UASO and controller communication may be unavailable if the control and communication links are shared or if the failure affects both links, such as an antenna failure, prohibiting the UASO from providing observables to the controller. Because of the potential of this lack of observables to the controller, some COAs require alternate communication architecture, such as a terrestrial or 'land' line. This may provide an enhanced opportunity for controller re-convergence compared to NORDO manned aircraft. Yet land lines currently used likely increases time delay between lost link and the controller receiving such an observable as discussed in 9.2.2.2 Lost Link. Second, the UASO may be unaware of the unmanned aircraft's lost link intent due to their lack of UA intent observables once lost link occurs. While lost link procedures are often predefined based on flight plan segment, some UA are able to change intent during their lost link procedure, dependent on component inoperability such as engine loss or electrical failure, the aircraft's current position, or automation capability (Eurocontrol, 2010; Federal Aviation Administration, 2013). If the UA changes lost link intent, the UASO may incorrectly infer UA intent without a real-time intent observable. To illustrate, Figure 10-3 shows the RQ-4 Global Hawk flight plan, consisting of waypoints that each have up to four contingency routes beyond the nominal flight plan. Instead of the UA following a C1 "Link Out" routing as the controller may infer, the UA may follow a C3 "Land Now" routing. The UASO may then provide an inaccurate observable to the controller regarding UA intent, propagating divergence as illustrated earlier in Figure 8-5.

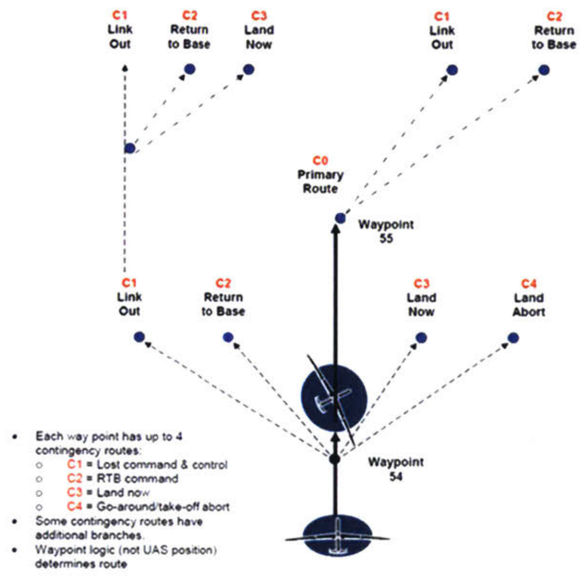

Figure 10-3. Lost link conditional routing (Eurocontrol, 2010).

Another approach in current operations is to transmit a discrete transponder beacon code when the unmanned aircraft senses it has lost control link in order to inform the controller; current regulations block '7400' as this code (Federal Aviation Administration, 2015). Discrete transponder codes have been used during some UAS flights in the NAS and in research simulations, but the controller may still be vulnerable to perception failures of these observables leading to divergence regarding lost link status (either delays in perceiving changed transponder code or failure to perceive the change altogether). Simulations involving radar controllers monitoring UAS during flight yielded an average time from an unmanned aircraft transmitting a discrete transponder code regarding lost link status to the controller's perception of this code of 71 seconds (Kamienski, Simons, Bell, & Estes, 2010). If the lost link procedure included a maneuver towards a conflicting aircraft, this may not provide enough time for the controller to mitigate the potentially hazardous situation to prevent a hazardous consequence. Transponder code observables alone for lost link status may not be sufficiently salient to capture the controller's attention, which would be considered a perception failure in the cognitive process framework. Exacerbating the lack of perception of the observable is the possibility of the UA continuing its current clearance, providing no additional observable such as clearance non-conformance to bring attention to the aircraft. Also, the discrete transponder code does not provide intent information to aid in aircraft position projection. Observables missed by the controller can propagate from a perception failure to a lack of awareness of lost link status. If the controller is unaware the UA is lost link, the controller may incorrectly project the UA's future position, leading to potentially the same consequential divergence and hazardous situations described earlier.

Some SOPs provide lost link intent, but lost link procedures can change in flight due to re-routing, weather, or traffic (Rabe, Abel, & Hansman, 2016). There is currently no mechanism to provide the controller updated lost link intent beyond post-lost link UASO communications. Controllers may still be vulnerable to divergence regarding lost link intent if new intent observables are not perceived by them. The lack of these observables may lead a controller to use static knowledge sources from SOPs to infer lost link intent. The lack of these observables would be considered a perception failure propagating to a comprehension failure in the cognitive process framework. A lack of UA intent awareness could propagate to a projection process failure, leading to a lack of awareness of the UA's future position. Divergence regarding the UA's future position could lead to potentially hazardous consequences as described earlier.

10.2.3 Potential Mitigations for Lost Link

One approach to mitigate the causes of controller divergence due to no, inaccurate, or ambiguous observables is to improve the information content, accuracy, and distinctness of observables controllers receive, such as lost link status and lost link intent that are consequential. To accomplish this and potentially reduce time delay, technologies and procedures for the UA to send lost link status and intent observables directly to the controller could be implemented. In general, observable considerations include their salience and how continuously they are displayed. In addition, they should be able to alert the controller and provide the controller state values directly rather than coded observables via a language easily perceived and comprehended, such as those conveyed via CPDLC.

Currently, lost link intent is distributed as shown in Figure 10-4. The UASO (blue) programs lost link intent to the UA (red) and provides it to the controller (green) when lost link occurs. The controller also receives UA position real-time.

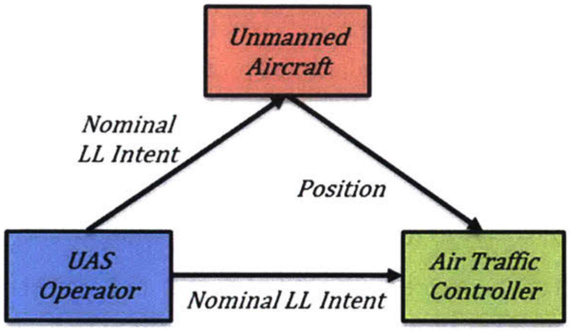

Figure 10-4. Current nominal lost link intent observable architecture.

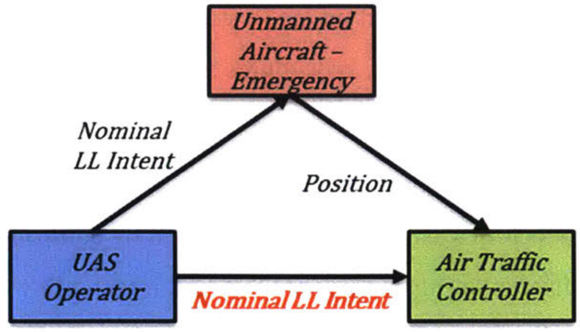

Figure 10-5. Ineffective lost link intent observable architecture.

If the UA changes intent during lost link, the current architecture may lead the UASO to provide an inaccurate observable to the controller, highlighted in red in Figure 10-5 and discussed earlier. The UASO may provide nominal lost link intent while the UA flies a different procedure or the controller may not be provided with any observables due to communication loss. Observables directly from the UA to the controller are shown in Figure 10-6. If a lost link procedure changes, the controller may receive a more accurate, unambiguous observable while likely minimizing time delay. This would aid controller convergence regarding lost link status and intent, helping the controller accurately project future UA position. However, this mitigation requires the UA to provide observables to the controller during lost link, which may be in question considering link interdependencies. Although less informative, multiple discrete transponder codes for conditional lost link intent could be used, such as 7401 = "return to base," 7402 = "continue to destination," etc.

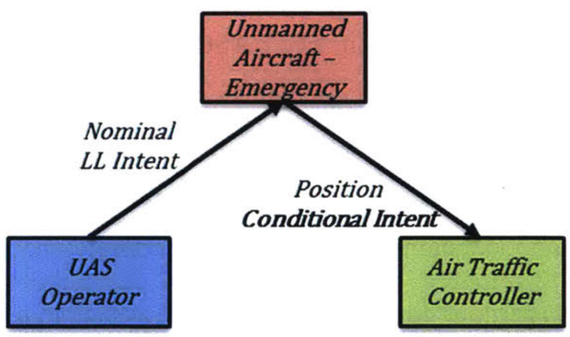

Figure 10-6. Proposed UA LL observable communication architecture.

Another approach to mitigate the causes of controller divergence from a lack of perception is to continue to leverage the fact that the UASO is likely on the ground. Mitigations could include mandating alternate communication architecture independent of normal UAS communications. This was cited in the ATC UAS field study as a valuable means of communicating numerous observables between the controller and UASO during contingencies, which is not available when manned aircraft are NORDO. However, procedures should ensure rapid and direct communications between controllers and UASOs are established to limit misunderstandings, taking into account the command and control architecture of UAS and ATC systems. Procedures should aid comprehension by developing standardized protocols to communicate lost link intent with syntax and terms of use.

Another approach to mitigate the causes of divergence from a lack of perception is to use lost link trajectories as observables perceived by controllers on their displays to reduce the ambiguity when differentiating conditional lost link intent, allowing controllers to comprehend lost link intent and project UA position more accurately. To explain, nominal lost link could require a trajectory change from the UA's current clearance, while UA lost link coupled with engine failure would produce a different trajectory immediately. Therefore, current UA trajectories provide future UA intent. However, this mitigation may produce potentially hazardous situations unanticipated by ATC by initiating a potentially hazardous situation, such as an aircraft-to-aircraft conflict, and it may still be ambiguous. Another option to provide distinct lost link observables may include a combination of UA communication when lost link occurs and the aircraft's lost link intent logic, allowing ATC automation to detect and integrate observables to display future UA position to the controller directly.

Mitigating hazardous consequences after controller divergence can be accomplished by transforming the divergence to inconsequential. Transforming divergence to inconsequential may be possible if the UA is segregated from conflict following lost link by safely removing itself from the consequential situations, including segregation from other aircraft, terrain, obstacles, and sever weather.

Another approach to mitigate hazardous consequences is to promote controller re-convergence so controllers can provide a correct recovery action. The UASO or UA could communicate lost link status and intent to provide a means for controller re-convergence, accomplished via communication channels described earlier. Also, research to integrate UA CPDLC, transponder codes, and lost link flight plans may allow ATC automation to provide alerts for aircraft-to-aircraft conflicts. These alerts could include graduations of urgency or likelihood, beginning with clearance conformance monitoring to future LoSS.

Another approach to mitigate hazardous consequences is for the system to provide mitigation from hazardous consequence without controller or pilot intervention. Independent onboard control automation that continued to function during lost link to mitigate potentially hazardous situations is one method. These systems include aircraft-to-aircraft conflict alerting (ACAS) and aircraft-to-terrain conflict alerting (TAWS), should be compatible with manned aircraft, and useable during all UA states including lost link or other emergencies. These procedures may include proceeding to a safe airspace and geo-fence, via horizontal and vertical constraints, or flight termination at an uninhabited location.

10.3 UAS Flight Characteristics

Currently, UAS designs are optimized differently than manned aircraft, including flight profiles such as loitering and grid patterns compared to more typical point-to-point transit and static, long-duration flight, and performance characteristics with lower cruise speeds and increased maneuverability. These missions have traditionally been confined to SUA (Rabe, Abel, & Hansman, 2016), which are designed to segregate disparate and incompatible types of aviation,[65] where controllers do not typically control. The discussion of these UAS challenges is divided into three sections: flight profiles with more complex or less structure routes, flight profiles with static, long-duration missions, and performance characteristics.

10.3.1 UAS Flight Profiles – More Complex or Less Structured Routes

Some current UAS missions have unique flight profiles, such as loitering and grid patterns.[66] Loitering includes pre-defined navigation paths, such as a 'race-track' or 'orbit' shown in Figure 10-7, and undefined navigation paths, such as random patterns.[67] A potential grid pattern is shown in Figure 10-8.

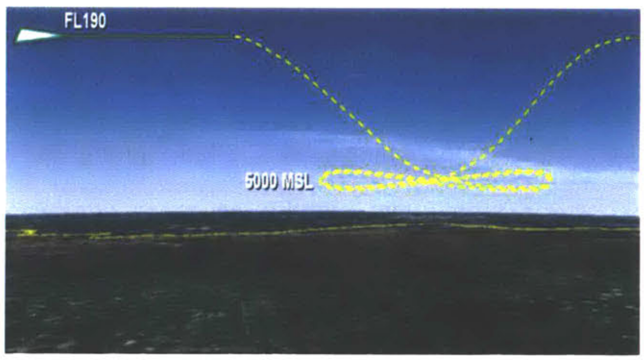

Figure 10-7. Loiter pattern (FAA, 2012).

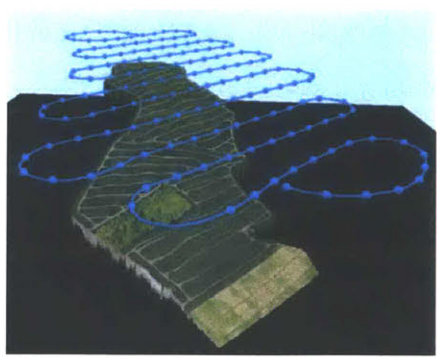

Figure 10-8. Grid pattern (UAS Magazine, 2017).

[65] Special Use Airspace is "airspace wherein activities must be confined because of their nature" (FAA, 2014).
[66] "While in a grid pattern, an aircraft flies a back-and-forth route such as north-to-south or east-to-west within a contained area. Grid patterns may occur in any class of airspace, controlled or uncontrolled" (FAA, 2012).
[67] "Loitering occurs when an aircraft remains within a given volume of airspace. Loitering is typically used for search and surveillance operations, which may use random patterns, but may also include flying a 'race-track' or 'orbit.' Loitering differs from airborne holding in that airborne holding is one of the capacity and/or workload management techniques used by ATC, while loitering is specific to the mission of the flight" (FAA, 2012).

10.3.1.1 Controller Divergence Vulnerabilities for UAS Flight Profiles

Some UAS operations may involve complex, yet predictable navigation profiles such as a grid pattern, while other flight paths may be less structured or completely unpredictable, such as loitering above an area. Flight profiles in UAS result in an increased risk of controller divergence regarding future aircraft position due to projection difficulties for a number of reasons. First, these types of flight operations are currently incompatible with ATC flight plan and clearance interfaces within the US (Paczan, Cooper, & Zakrzewski, 2012). Work arounds for more complex navigational paths and less-structured operations than traditional structured routes are currently required and may lead to a lack of or ambiguous observables relating to aircraft intent, leading to a perception failure vulnerability increasing position projection challenges. In addition, automation systems to aid projection are currently not robust to UAS flight profiles or navigational complexity (Paczan, Cooper, & Zakrzewski, 2012; Hampton, 2014).[68] These navigational paths may also be more challenging to project by the controller for two reasons. Aircraft in turns (i.e. accelerating) are harder to project than aircraft flying constant velocity, linear paths because object acceleration is difficult to cognitively integrate into projection (Gottskanker & Edwards, 1956; Wekhoven, Snippe, & Toet, 1992; Davison Reynolds, 2006). Also, controllers may not have developed a mental model for this projection which is usually built through training and experience. These challenges could lead to a projection process failure as described in the cognitive process framework, which could propagate to a lack of awareness of future UA position. If the controller is unaware of future UA position that may be in conflict with other aircraft, terrain, obstacles, or significant weather, this could result in consequential divergence and the controller could execute a hazardous action. In addition, once the controller is diverged the lack of observables and more challenging projection may not promote controller re-convergence as well. Divergence vulnerabilities due to atypical flight profiles are illustrated by the framework in Figure 10-9.

[68] Interface limitations occur when the flight plan includes delays based on number of orbits or amount of fuel rather than time, too many route waypoints, the reuse of a route point, or exceeds the maximum flight plan time. Also, current flight plan interfaces due not include many UAS loiter configurations or contingency route planning.

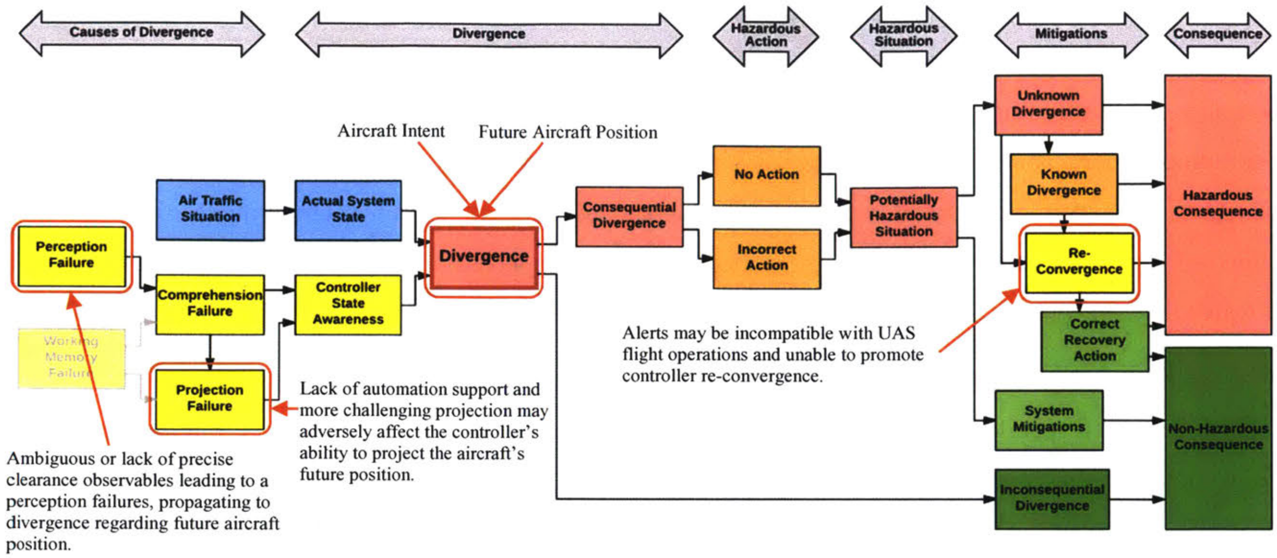

Figure 10-9. Vulnerabilities due to UAS flight profiles.

10.3.1.2 Potential Mitigations for UAS Flight Profiles

One approach to mitigate the cause of controller divergence from a projection failure is to allow structure to reduce the precision at which controllers are required to project future position, thus increasing the magnitude of divergence before it becomes consequential. One way to accomplish this is to create and display "segregated-area abstractions," which could provide controllers an airspace volume the UAS will fly within for a specified time for complex yet predictable but especially unpredictable flight paths. This allows the controller to project the aircraft's future position less precisely while still allowing them to project sufficient separation between the unmanned aircraft and other structured routes. However, this mitigation may be limited in its practicality before a "segregated-area abstraction" interferes with too much airspace or intersects with structured routes. These "segregated-area abstractions" could provide lateral and vertical structure boundaries for the aircraft's future position in unstructured shapes. Figure 10-10illustrates an example lateral-only structure for future UAS positions within a specified time.

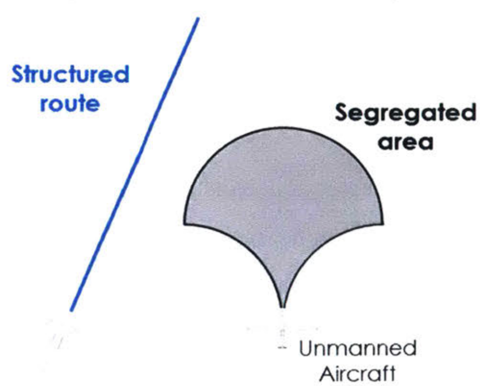

Figure 10-10. Segregated area abstractions.

To accomplish this mitigation, along with others which will be discussed, controller displays and automation should be compatible with UAS flight plans, updated clearances, contingency information, and new structural mitigations. With compatibility, automation systems could provide future UAS position or other abstractions as an observable state. If explicitly providing future states are unfeasible, designers could provide controllers additional current state information such as climb and turn rate to support mental simulation to increase projection accuracy. Displayed information should be oriented towards the controller's goals, such as separation between the UA and other hazards.

Another approach, especially for complex yet predictable flight paths, includes interfaces which provide more precise and specific flight plan clearances as additional structure to aid projection. Flight plans could specify enough detail for accurate controller projection, such as additional waypoints, limiting the projection required during turning or accelerating flight, or controller displays could provide complex structure to aid controller projection. For instance, given a 'figure-8' orbit around two waypoints on the left-hand side of Figure 10-11, additional waypoints provide the controller near-linear interpolation on the right-hand side, or the lines themselves could be added to the display similarly to the left-hand side.

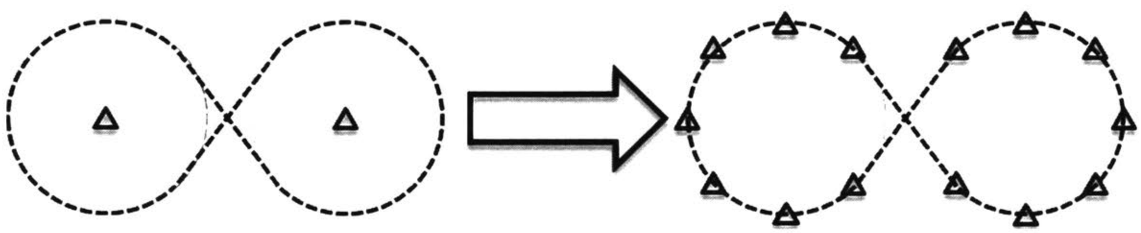

Figure 10-11. Additional waypoint structure.

Mitigating hazardous consequences after controller divergence can be accomplished by transforming the divergence to inconsequential. Controllers' requirement for UAS position projection could be inconsequential if separation responsibility was delegated to the UAS or if incompatible UAS could be segregated from other aircraft, but delegated separation and segregation fails to solve UAS-integration. However, segregated airspace blocks could be used 'tactically' as discussed earlier and illustrated in Figure 10-10 as a means to reduce hazardous consequences during periods of high divergence likelihood or more atypical flight profiles.

Another approach to mitigate hazardous consequences is to promote controller re-convergence. Using integrated flight plan and clearance information to improve alarms that alert the controller of future losses of separation may be possible. Potentially less robust, procedures for agents to provide future separation observables to the diverged controller could be developed. For instance, architecture could downlink impending losses of separation to the controller from the UA itself or the UASO could communicate future losses of separation to the controller. During periods of controller known divergence, procedures could enable controllers to elicit future position or separation information from the UASO or UA.

Another approach to mitigate hazardous consequences is for the system to provide the mitigation independent of the controller. UAS could provide independent alerting of future losses of separation or significant weather penetration to the UASO as discussed in 10.1 Lack of Onboard Human Perception. Also, technologies and procedures could be developed to aid aircrew in onboard perception of potentially hazardous situations using VLO techniques and technologies, such as synthetic vision systems, enhanced vision systems, and high visibility aircraft technologies. These may be more important with UAS, which may have smaller surface areas and radar cross sections.

10.3.2 UAS Flight Operations – Static, Long-Duration Missions

UAS may fly long-duration missions in the same geographic region likely controlled by the same sector controller, which may lead to less frequent radio communications compared to point-to-point transit. Also, operators may wish to fly the UA in roughly the same position above the ground, resulting in the UAS not traversing the TSD as quickly as point-to-point transit profiles.

10.3.2.1 Controller Divergence Vulnerabilities for UAS Flight Operations

UAS flight operations, such as long-duration flight over the same geographic region, may result in an increased risk of working memory failures regarding the existence of an aircraft leading to controller divergence. Although an aircraft's existence is usually continuously displayed, a controller scans information serially while keeping information recently perceived in working memory (Shorrock, 2005). Research suggests that aircraft memory failures are related to the amount of control exercised on an aircraft (Means, et al., 1988; Gronlund, et al., 1997; Gronlund, Ohrt, Dougherty, Perry, & Manning, 1998; Shorrock, 2005), and more forgotten aircraft include "overflights, 'lows and slows', and aircraft on the pilots' own navigation or on a radar heading" (Shorrock, 2005), supporting increased likelihood of memory failures with less radio communications, slow groundspeeds,[69] and aircraft on their own navigation. These memory challenges could lead to a working memory failure as described in the cognitive process framework, which could propagate to a loss of awareness of an UA. If the controller is unaware of an UA that may be in conflict with other aircraft or significant weather, this could result in consequential divergence and the controller could execute a hazardous action. Figure 10-12 shows a notional TSD with an UA at zero groundspeed and three other aircraft at typical groundspeeds.

[69] The velocity of aircraft traversing the TSD may directly affect attention, increasing the likelihood of working memory failures. Research suggests mean aircraft velocity positively correlates to mean saccadic velocity (Cong, Hu, Dong, Liu, & Wang, 2016). If saccadic velocity decreases, which should occur at lower aircraft velocities, the mean fixed duration of aircraft attention will increase, potentially decreasing rehearsal rates and increasing the likelihood of working memory failures.

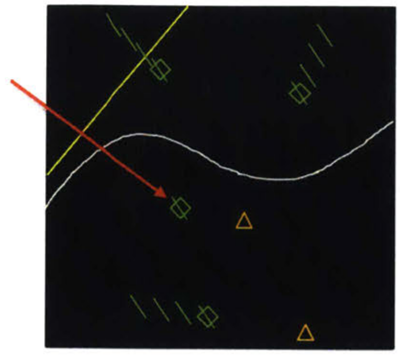

Figure 10-12. Notional aircraft with zero groundspeed.

Divergence vulnerabilities due to atypical flight operations are illustrated in Figure 10-13.

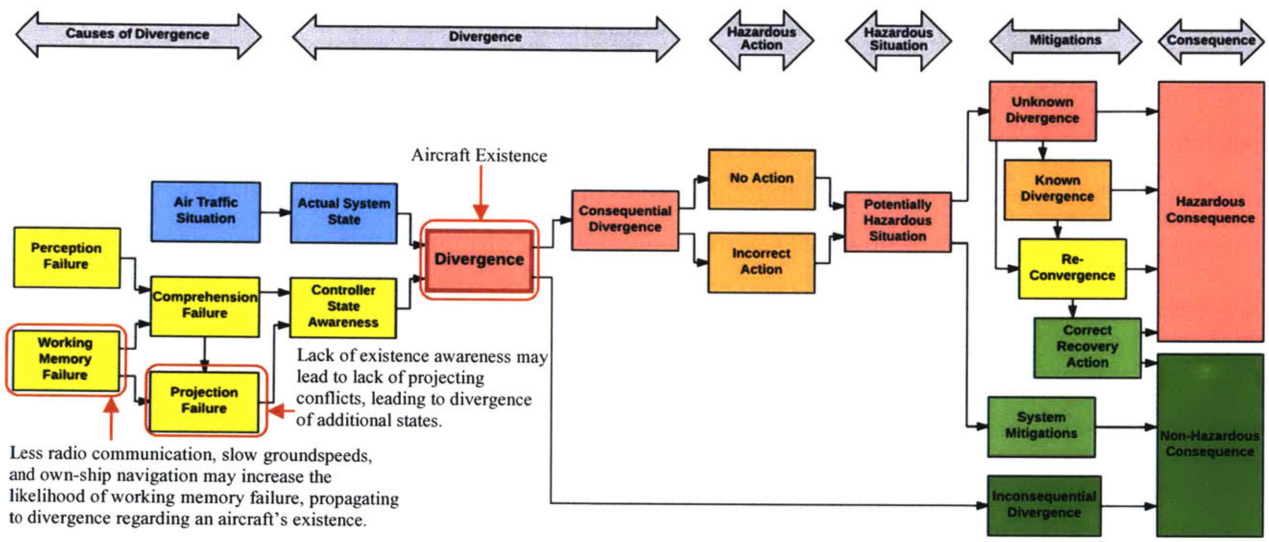

Figure 10-13. Vulnerabilities due to atypical flight operations.

10.3.2.2 Potential Mitigations for UAS Flight Operations

One approach to mitigate the causes of controller divergence from a working memory failure is to ensure the continuous presentation of aircraft. While this is already attempted, surveillance systems, displays, and automation should be compatible with UAS and their characteristics, such as speed and trajectory. Although not unique to UAS, these systems should be robust to failures, such as a transponder failure, and still present the UAS using other means. However, UAS groundspeed, size, and radar cross section may present challenges to this goal.

Another approach includes procedures requiring intermittent controller-UAS interaction. For example, procedures could mandate controller communication with UASOs at specified time intervals or based on controller attention lapses sensed via eye-tracking or other technologies. Or, controllers could interact with their displays regarding the UA; for instance acknowledging the UA at specified time intervals, attention lapses, or during otherwise consequential moments.

Mitigating hazardous consequences after controller divergence can be accomplished transforming the divergence inconsequential by delegating separation or segregation as described in 10.3.1.2 Potential Mitigations for UAS Flight Profiles. Another approach to mitigate hazardous consequences is to promote controller re-convergence of the aircraft's existence by alerting the controller of potentially hazardous situations via automated alarms or communication from other agents in the system, as previously discussed. Again, these alerts should be compatible with UAS speeds, trajectories, and surveillance capabilities and contingencies. Another approach to mitigate hazardous consequences is for the system to provide mitigation, similarly as referenced in 10.3.1.2.

10.3.3 UAS Performance Characteristics – Low Speeds and Increased Maneuverability

As described in Chapter 1, aircraft velocity differences between manned and unmanned aircraft was the controllers' most often cited factor, where all stated UA's slower velocity was a challenge in their integration with manned and higher-speed aircraft, especially when combined with their inability to accept visual separation clearances. Also, the lack of humans onboard and UAS sizes and weights could bring increased maneuverability in future designs, which may manifest in atypical turn or climb rates.

10.3.3.1 Controller Divergence Vulnerabilities for UAS Performance Characteristics

Atypical performance characteristics, such as slower velocities and increased maneuverability, result in an increased risk of controller divergence regarding future aircraft position due to projection difficulties for a number of reasons. Position projection may prove more challenging based solely on atypical speeds, especially slower speeds. Objects moving at slower speeds often result in an overestimation of velocity (Gottskanker & Edwards, 1956; Castet, 1995; Xu, Wickens, & Rantanen, 2004; Davison Reynolds, 2006). Also, humans adapt to a particular speed range (Smith, 1985; Smith, 1987; Davison Reynolds, 2006), and develop a mental model of aircraft speeds, which UAS speeds may be outside of the controller's typically viewed range. In addition, when controllers separate aircraft traveling at different speeds, a 'distance-over-speed' bias can influence the controller to estimate a closer, slower aircraft will reach an intersection or pass in front of a farther, faster aircraft (Xu, Wickens, & Rantanen, 2004). Finally, projection automation aids may not contain UAS performance parameters and assumptions made for automation may be substantially different with UAS.

As discussed earlier, accelerating aircraft are also harder to project. Increased maneuverability with no change in the position sample rate, currently 4.8 or 12 seconds for radar surveillance systems,[70] may adversely affect controller projection accuracy. Aircraft turn and climb rates are not provided on displays

[70] Radar surveillance systems in the terminal area, such as ASR-7, -8, -9, and -11 provide an update rate of 4.8 seconds (Davison Reynolds, 2006), while update rates in the enroute airspace by Air Route Surveillance Radar (ARSR) are 12 seconds (MIT Lincoln Laboratory, 2006).

and are inferred based on three-dimensional position updates to extrapolate aircraft future position, which is more challenging than linearly extrapolating position. Yet future UAS may change their heading or altitude more quickly than manned aircraft between surveillance updates. An example of increased turn rates with low sample rates is shown in the two aircraft in Figure 10-14. Each '\' signifies a previous position sample and may be used by the controller to infer future position. The aircraft proceeding from top to bottom of the figure is more easily projected while the aircraft turning at the bottom of the figure is more challenging to infer heading and future position possibly due to position locations not perceived by the controller with the sample rate. Therefore, current surveillance update rates may be too infrequent to accurately extrapolate future aircraft position with potentially increased UAS maneuverability.[71]

Figure 10-14. Notional increased maneuverability on the TSD.

These challenges could lead to a projection process failure as described in the cognitive process framework, which could propagate to a lack of awareness of future UA position. If the controller is unaware of future UA position that may be in conflict with other aircraft, terrain, obstacles, or significant weather, this could result in consequential divergence and the controller could execute a hazardous action. Also, the lack of observables and more challenging projection of atypical performance characteristics may adversely affect the diverged controller's ability to re-converge. Divergence vulnerabilities due to atypical performance characteristics are illustrated in Figure 10-15.

[71] Surveillance update rates versus aircraft acceleration affect controller projection error (Davison Reynolds, 2006).

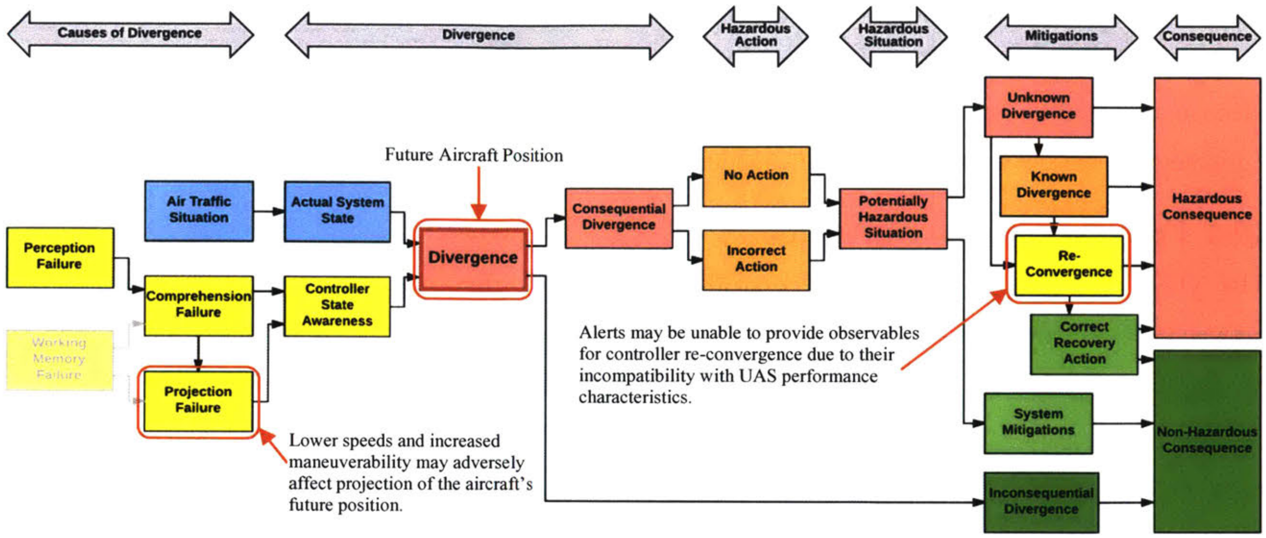

Figure 10-15. Implications for atypical performance characteristics.

10.3.3.2 Potential Design Considerations

The approaches to mitigate the causes of controller divergence from a projection failure where described previously in 10.3.1.2 Potential Mitigations for UAS Flight Profiles, such as developing and displaying structure to aid in position projection, ensuring automation aids include atypical UAS performance characteristics, and increasing UAS typicality during areas of known conflict, such as merge points, by mandating turn rates, climb rates, or airspeeds as shown in Figure 10-16.

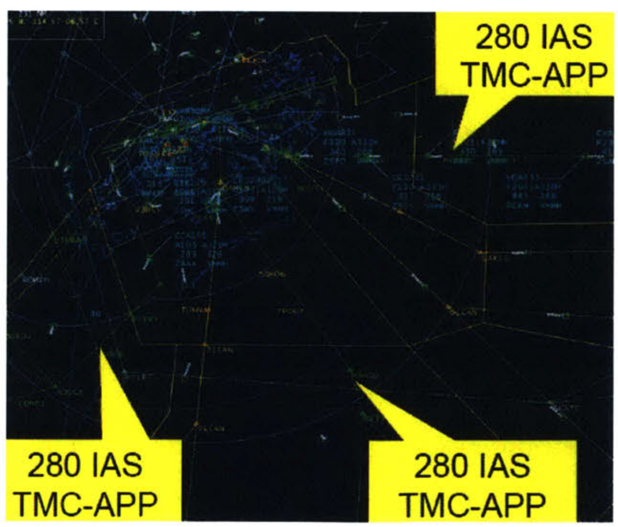

Figure 10-16. Mandated airspeed points during arrival sequencing (Civil Aviation Department, 2017).

Another approach includes increasing surveillance update rates to enable accurate position projection, possibly decreasing projection error between samples. A possible solution is through ADS-B, which updates once per second (Federal Aviation Administration, 2017), or designers could provide automation systems that would present future UAS position directly as previously discussed.

Mitigating hazardous consequences after controller divergence can be accomplished similarly to previous sections of 10.3 UAS Flight Characteristics by providing structure or procedures that lead to inconsequential divergence, promotes controller re-convergence, or provides ways for the system to mitigate the hazardous consequence independent of the controller.

10.4 Levels of Control Automation

The ATC UAS field study highlighted controllers' opinion of differences in levels of control automation between MQ-1/9 and RQ-4 that affected their control strategies. Future UAS operations could utilize levels of control automation not previously available to manned aircraft, which may affect the state awareness and task of the controller, leading to both opportunities and divergence vulnerabilities. One level of control automation could be fully autonomous, yet non-adaptive, where the UA would fly a pre-programmed profile unable to change the flight plan or adapt to external disturbances.[72] Another level of control automation, such as the RQ-4 Global Hawk, have a high level of supervisory control using keyboard inputs for waypoint-to-waypoint or pre-programmed routes.

10.4.1 Opportunities and Divergence Vulnerabilities from Various Levels of Control Automation

Fully autonomous, non-adaptive UA present a convergence opportunity for controllers regarding aircraft intent. The lack of variability of aircraft intent could reduce the likelihood of perception failures due to the lack of observables or lack of perception of changing intent. For example, the controller could receive a detailed aircraft flight plan prior to flight initiation, which would not change during the flight, reducing the vulnerability for incorrect states input to the projection process for aircraft position projection. With more accurate future state awareness, controllers may plan and execute more appropriate commands to maintain aircraft separation from hazards. However, the same projection vulnerabilities discussed in 10.3 UAS Flight Characteristics would still apply. On the other hand, diverged controllers may be vulnerable to continued divergence regarding aircraft intent because they lack the option to command an intent state to re-converge, but would only be able to elicit intent information from the UA or UASO, if available (less ability for controllers to mitigate hazardous consequences). Communication architectures may not be available for the UA to provide additional observables to the controller or the UASO may not be aware of the UA's state to provide accurate observables to the controller since they may have decreased state awareness due to the increased autonomy level (Cummings, Bruni, Mercier, & Mitchell, 2007; Porat, Oron-Gilad, Rottem-Hovev, & Silbiger, 2016). This could lead to a continued known diverged controller, unable to mitigate a hazardous consequence if a potentially hazardous situation had developed. Also, the

[72] The FAA has proposed that this level of control automation is unacceptable for IFR operations integrated in the NAS due to their lack of flexibility (FAA, 2012), but considerations are discussed.

UASO or UA may not be able to mitigate the hazardous consequence (system mitigation) themselves due to full autonomous control.

Semi-autonomous supervisory control, such as the RQ-4 Global Hawk, present divergence vulnerabilities for controllers regarding future aircraft position due to the controller's lack of a developed mental model. As stated in the ATC UAS field study, controllers perceive response latency and a lack of flexibility regarding an aircraft's resultant actions following a commanded maneuver. This could present more uncertainty in aircraft response projection and overall inaccurate future aircraft position projection following a commanded action. Divergence vulnerabilities due to various levels of control automation are illustrated by the framework in Figure 10-17.

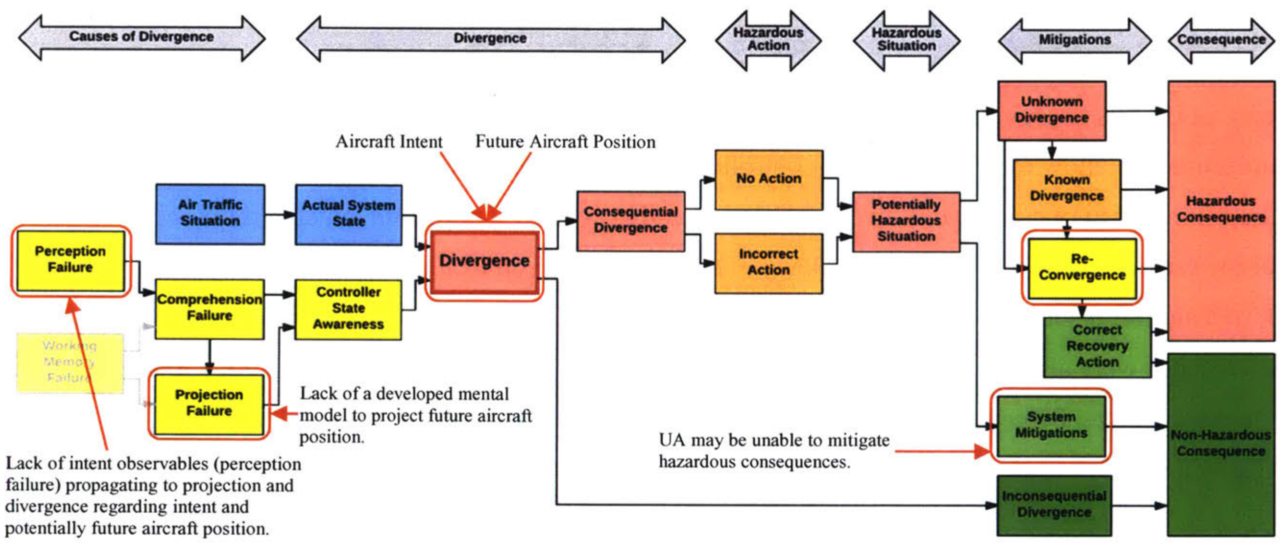

Figure 10-17. Vulnerabilities due to fully autonomous and adaptive control automation.

10.4.2 Potential Mitigations for Various Levels of Control Automation

To fully realize the opportunities for controllers managing fully autonomous non-adaptive control architectures on UA, the controllers should receive a detailed UA flight plan with precise intent state variable values, such as airspeed, altitudes, etc. With this information, robust ATC automation systems could provide more accurate predictive aiding of future UA position to be used by the controller to offset the negative effects of fully autonomous non-adaptive control architectures on UA, such as their inability to follow controller commands. Segregating non-adaptive UA from other aircraft flight routes provides a means to transform future aircraft position divergence from consequential to inconsequential, rendering divergence inconsequential by not allowing a consequential situation to develop.

Another approach to mitigate hazardous consequences is to promote controller re-convergence so controllers can provide a correct recovery action. While a correct recovery action could only be provided to a non-autonomous aircraft, alerts detecting aircraft trajectories and providing observables to the controller, as described in 10.1.2 Potential Mitigations for the Lack of Onboard Human Perception, could provide a potential solution. Another approach to mitigate hazardous consequences is for the system to provide mitigation. The UA could incorporate avoidance systems for other aircraft, terrain, obstacles, and sever weather as described in 10.1.2 Potential Mitigations for the Lack of Onboard Human Perception as well. Also, mitigations could be similar to considerations provided in CFR Part 101 for moored balloons, kites, amateur rockets, unmanned free balloons, and certain model aircraft since once the UA is released, it is also not positively controlled (Code of Federal Regulations, 2017). These considerations include restricting flight in densely-populated areas, weight and impact force restrictions (i.e. small mass), high visibility techniques, operating only in high visibility environmental conditions (i.e. VMC), and prior notification through NOTAMs and other structured procedures.

One approach to mitigate the causes of controller divergence regarding semi-autonomous supervisory control UAS is to provide feedback mechanisms regarding specific aircraft intent and the timeliness of maneuvers to allow for more accurate controller projection. In addition, this could provide observables for the controller to re-converge if divergence has already occurred. Training to develop these mental models of the various types of UAS and their level of control automation would enhance their ability to project future aircraft position. In addition, approaches to mitigating hazardous consequences after controller divergence were also discussed in previous section, including 10.1.2 Potential Mitigations for the Lack of Onboard Human Perception, 10.2.3 Potential Mitigations for Lost Link, and 10.3 UAS Flight Characteristics.

10.5 Summary

The previous four vulnerability areas highlight key issues associated with UAS integration. Aircraft intent appears to be an important state that is vulnerable to controller divergence during lost link, UAS flight profiles, and various levels of control automation. This state appears vulnerable to perception failures due to a lack of an observable to provide intent, which can propagate to a projection failure of the future aircraft position and future separation with other aircraft and significant weather and to a lesser extent terrain and obstacles. Also, future aircraft position may be more challenging to accurately project and appears vulnerable to divergence due to potentially more complex navigational flight paths or less structure and less predictable navigational flight paths, along with UAS performance characteristics. Finally, hazardous consequences may be more likely for UAS operations due to the inability for UAS to mitigate hazardous consequences themselves. At times, the UASO may have less awareness of a hazardous consequence. Other times, the UA may be fully autonomous and unable to take action to mitigate hazardous consequences.

10.5.1 Implications for Future UAS-Integration

Insight gained from the ATC case study, ATC UAS field study, and UAS-integration study to mitigate the causes and consequences of controller divergence may be valuable for how future UAS-integration procedures, training, and technology are developed. These approaches to mitigation address the need for NAS-wide standardization of procedures and information technologies for ATC clearances and their interfaces, the development of lost link procedures which can provide predictable responses for the controller, and the development of procedures, technologies, and architectures for UAS traffic and weather information sharing capabilities.

Based on results from the ATC UAS field study, UAS procedures have been developed locally and are inconsistent between different operating facilities and between different UAS types. However, as UAS become integrated throughout the NAS a larger amount and wider variety of UAS types will likely be interacting with more control facilities across the US, increasing the complexity of these operations. To reduce the burden on controllers' long-term and working memory regarding knowledge of various UAS types and their operations, the NAS may require the standardization of interfaces, procedures, and communication at the NAS level. This standardization could help reduce controller divergence likelihood by requiring less knowledge stored in long-term memory and enabling more developed mental models to comprehend and project UAS states, along with allowing more developed expectations and a reduction in workload during UAS operations.

Interfaces to receive and display information from the UASO to the controller, specifically flight plan clearances, should be standardized and compatible between UAS and ATC systems. During the field study controllers stated they require knowledge of whether an aircraft is manned or unmanned. One reason cited for this was the aircraft's ability (or lack thereof) to see-and-avoid, thus changing controllers' strategies and procedures. Also, some controllers wanted to identify aircraft type to determine the aircraft's level of control automation, either remotely piloted through a stick and throttle or more highly automated keyboard control. Other research has highlighted the controllers' need for the type of communication link (Yuan & Histon, 2014). This information could be delivered by the UASO when a mandated UAS flight plan is filed and be visible to the controller via their flight progress strip or data-block on their display to allow for a more precise mental model without further burdening working memory. Also, current flight plan and clearance interfaces such as ERAM (En Route Automation Modernization) along with ATC automation systems are not compatible with the size and type of UAS flight operations due to limited waypoints and navigational complexity (Rabe, Abel, & Hansman, 2016). The North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 4586 provides data elements and message formats likely needed to manage complex UAS flight operations (Paczan, Cooper, & Zakrzewski, 2012). These may be complex three- or four-dimensional navigational paths similar to Area Navigation (RNAV) routes which would likely benefit from architecture with compatibility between UASO route planning/programming interfaces to ATC management systems in order to share flight plan routes while reducing the potential for task saturation or human input errors during manual information transfers.

Another major divergence vulnerability area requiring attention is lost link operations. From the UAS-integration study, aircraft intent and future aircraft position appear to be important states that could be challenging for controllers to comprehend and project due to lost link. Currently, lost link procedures for communicating lost link status and the aircraft's trajectory following lost link are developed locally and differ between types of UAS and between operating locations within the USAF. However, continuing with locally developed procedures may increase long-term and working memory challenges leading to divergence of lost link status and intent when UAS variation increases at facility locations and more controllers interact with them nationally. To increase the likelihood of controllers comprehending that lost link has occurred, a method of immediate notification of loss of control link must be developed that is both salient and robust to compounding failures of lost link due to the potential immediate change of aircraft intent and trajectory. Beyond UASO voice or data communications which may also be vulnerable during lost link, potential mitigations include discrete transponder beacon codes, ADS-B messaging, data communications such as CPDLC, or direct messaging from the unmanned aircraft to ATC. Also, UASOs should be able to immediately contact ATC through alternate communication methods if traditional methods fail. Previous potential mitigations discussed for communicating lost link status (e.g. data communications) could also immediately down-link lost link intent in a useable format for integration with ATC systems to update clearance information or automation aids for future position projections. To reduce the burden of position projection, controllers may benefit from a lower variety of lost link procedures and research could determine a minimum number of standardized lost link procedures for UAS in the NAS. Considerations for this number include the various levels of automated landing capability, levels of automation for conditional intent during lost link (e.g. compounding aircraft emergencies which change the trajectory during lost link), and geographic location from lost link loiter points, divert contingency points, or flight termination points.

A vulnerability of the lack of onboard human perception among UAS is their potential inability to perceive potentially hazardous situations, such as aircraft-to-aircraft conflicts or significant weather penetration, and take action to mitigate them without controller intervention. To achieve an equivalent level of safety with manned aircraft, UAS should be able to perceive these threats and maneuver to avoid them independently. Currently, there is significant effort towards research in areas of sense-and-avoid systems to remain well clear and avoid collisions with other aircraft, including ground- and airborne-based systems. These systems should coordinate and be compatible with legacy (e.g. TCAS) and future manned collision avoidance systems. Based on the potential for fully automated UA, whether lost link or pre-programmed flight, these systems should be effective under operator and automated control. Mandating these systems may provide greater safety than current manned aircraft without collision avoidance systems because sense-and-avoid systems may perceive traffic in VMC and IMC depending on their sensors. Another approach to mitigate this vulnerability is through increased awareness for the controller along with mandating UAS participation with ATC. With increase ATC awareness of traffic, which could be gained through increased sensor capabilities or architecture with information sharing from other NAS users, controllers may be able to mitigate hazardous situations better.

UAS are also vulnerable to significant weather, particularly icing and turbulence (Rabe, Abel, & Hansman, 2016). Due to their lack of onboard human perception, UAS may require greater 'nowcasting' and forecasting of significant weather to remain well clear of these areas. One approach to mitigate is through enhanced controller awareness of these conditions through research regarding architectures to transmit and synthesize information from a variety of sources for more accurate and detailed weather state awareness. These sources could include enhanced procedures for eliciting or receiving manned aircraft PIREPs at specified time intervals or upon certain weather conditions, better ground- or space-based remote sensing capabilities of icing and turbulence potential, and icing and turbulence sensors onboard manned and unmanned aircraft to transmit data to ATC or another central facility. While research into better controller state awareness could reduce the potential for divergence, UAS must also be more robust for mitigating significant weather penetration if it occurs. As discussed before, UAS may benefit from systems that detect airframe icing and turbulence for not only transmitting this information to others, but also integrated with alerts to provide this state awareness to the UASO who can take action to avoid further weather penetration if necessary. Procedures for escape maneuvers to mitigate hazardous consequences once significant weather penetration occurs must be developed to satisfy the individual UAS and the effects of the maneuver within the context of the NAS.

Finally, the UAS field and UAS integration studies highlighted the divergence vulnerability with UAS operations and performance characteristics. To fully integrate into the NAS, development should consider the information, procedures, and training required for these characteristics. As discussed earlier, ATC management systems must be able to receive and use UAS operations and performance information to ensure appropriate inputs are provided to any decision support or conflict alert algorithms for ATC. Research should determine if these characteristics require new procedures and structure for UAS integration, including segregated areas for loitering patterns in the enroute environment or different procedures or approach routes for merging traffic to airports. Also, there may be a vulnerability of incorrect or underdeveloped mental models for aircraft position projection. Additional or different training methods may be required to accelerate mental model development while controllers gain experience with this new system. In addition, aircraft position projection may benefit from increased position sample rate which would decrease the inference required between samples and potentially reduce the error. ADS-B provides a potential solution which would update aircraft position once per second rather than once per 4.8 or 12 seconds as current surveillance radars provide.

11 Conclusions

This thesis extends the concept of divergence to the air traffic controller domain as a comparison between an air traffic controller's state awareness and the actual system state to understand the causes and consequences of controller divergence in an effort to identify potential mitigations. The concept of air traffic controller divergence was demonstrated to be a valid and useful approach to research air traffic controller vulnerabilities within the ATC system. To extend this concept to ATC, this research developed and applied a framework to better understand the causes and consequences of controller divergence which helped identify and understand patterns of divergence that were used to inform mitigations.

To accomplish this, the research developed the air traffic controller divergence cause and consequence framework and the air traffic controller cognitive process framework to fill the need to sufficiently investigate and understand controller divergence, which prior work could not provide. These frameworks provide a lens to examine human-integrated systems for divergence to reduce the likelihood of hazardous consequences occurring in a human-integrated system. Not only can the frameworks be used to further analysis of human error in accidents or incidents, but they can also be used in the development of new systems to identify potential areas of opportunity or vulnerability.

These frameworks were refined and utilized to examine the causes and consequences of controller divergence in ATC accident and incident case studies. To demonstrate the frameworks' utility, they were used to assess potential opportunities and divergence vulnerabilities resulting from introduction of UAS. First, UAS-experienced controllers were interviewed and observed to aid in determining areas of further investigation regarding the management of unmanned aircraft. Second, the frameworks were used to identify specific controller opportunities and divergence vulnerabilities within an UAS-integrated NAS.

11.1 Air Traffic Controller Divergence Cause and Consequence Framework

To extend this concept to ATC, the research was informed by prior work on risk analysis methods to develop an air traffic controller divergence cause and consequence framework. This framework representation was chosen because it focuses on divergence as a hazardous event and illustrates the causes and consequences of divergence, providing a structure for implementing mitigations for each. Developed from prior work by Reason (1990), the air traffic controller divergence cause and consequence framework provides a representation of the process and memory failures that can lead to inconsistent controller state awareness relative to the actual system state, defined by the air traffic situation. The cause and consequence framework also illustrates the pathways from controller divergence through their hazardous actions to the hazardous or non-hazardous consequence depending on the effectiveness of controller and system mitigations. After the diverged controller executes a hazardous action, the controller may transition to known divergence or re-converge, potentially executing a correct recovery action to affect the system towards non-hazardous consequences. Identifying the causes and consequences of divergence within the structure of the cause and consequence framework can aid in identifying potential mitigations for both. To better identify and understand the controller's contribution to the specific causes of divergence, an air traffic controller cognitive process framework was developed.

11.2 Air Traffic Controller Cognitive Process Framework

Also developed from prior work by Histon (2008), Endsley (1995), and Silva (2016), the air traffic controller cognitive process framework developed in this research integrates these previous models and adds a higher level of detail to the causes of divergence. Specifically, the cognitive process framework developed in this research describes a state assessment process that produces the controller's current and future state awareness, which is then used to determine divergence. The framework incorporates Silva's notion of a convergence/divergence comparator to accomplish this, as well as processes similar to Endsley's situation awareness and Pawlak et al.'s decision-making (Endsley M. R., Toward a Theory of Situation Awareness in Dynamic Systems, 1995; Pawlak, Brinton, Crouch, & Lancaster, 1996; Silva, 2016). ATC case study analysis described later refined the cognitive process framework as follows.

Because the air traffic controller's state awareness generally involves the projection of future states to inform their planning and accomplish their tasks, the future state projection was added to controller state assessment following the projection process. Due to the ATC case study analysis results, working memory was explicitly added to the framework to illustrate memory failures as a major cause of divergence following an otherwise consistent state assessment. Also, an abstraction of the concept of a mental model was added in each major cognitive process with knowledge input from long-term memory to allow for more precise determinations of the cause of divergence. In addition, expectations were shown in ATC case studies to be a large contributor to the controller's perception and comprehension processes, often times contributing to divergence. Finally, known diverged states were explicitly represented as a subset of controller state awareness and a divergence assessment process was added to compare observations to expectations and determine known divergence within the current state assumption. Known divergence was shown to affect downstream cognitive processes such as decision and execution.

These frameworks were utilized to better understand the causes and consequences of controller divergence in ATC accident and incident case studies to help identify and understand patterns of divergence which were used to inform mitigations. Figure 11-1 presents the additions made to the cognitive process framework in this research (shaded) beyond the integration between Histon's (2008) and Silva's (2016) models.

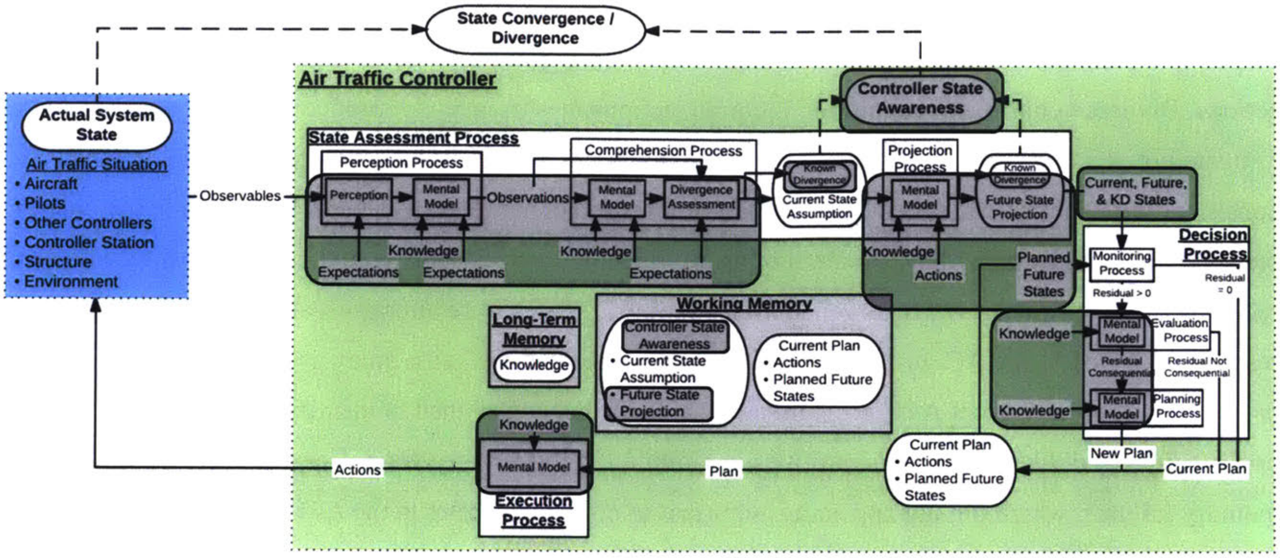

Figure 11-1. Contributions made to the cognitive process framework by this research.

11.3 Air Traffic Control Case Study Analysis

In order to refine and demonstrate the utility of the frameworks, this research analyzed ATC accidents and incidents where potential controller divergence contributed to the outcome of the situation. There were 42 NTSB cases with enough information to analyze between 2011 and 2015 where the air traffic controller contributed to an accident or incident. Of these, 27 cases (approximately 64 percent) contained controller divergence contributing to the hazardous consequence, highlighting the usefulness of this approach. Divergence was identified as not only an inconsistency in current states, but also future states as previously described, with all but 5 instances of divergence propagating to a divergence in future states before a decision was executed resulting in a potentially hazardous situation. These cases also provided a wide variety of causes and consequences of controller divergence, along with numerous diverged states. Case study analysis identified that all three state assessment processes, perception, comprehension, and projection, along with working memory of the current state contributing to controller divergence. This research highlighted the importance of downstream state assessment processes such as comprehension, projection, and working memory, which were not emphasized in previous research (Jones & Endsley, 1996). Controller mental models were found to be an important influence on divergence, contributing to divergence in 22 of 27 cases. The most common sources of process failures included a lack of perception of observables in perception, incorrect inference in comprehension, and incorrect knowledge in projection. The mechanism found most often to influence processes leading to divergence were expectation-driven biases, which led to divergence in 11 of 15 cases with perception or comprehension failures.

Diverged controllers provided both no or incorrect actions leading to potentially hazardous situations and all possible permutations of transitions through known divergence to re-convergence to correct recovery actions. Diverged controllers committed incorrect actions most frequently, producing rather than failing to mitigate potentially hazardous situations of which aircraft-to-aircraft conflicts were most common, consistent with controllers' tasks. Perhaps targeting resources at preventing controllers from being able to produce a potentially hazardous situation of an aircraft-to-aircraft conflict would be most cost-effective at reducing the consequences of divergence. In fact, 17 of 27 cases were aircraft-to-aircraft conflicts resulting in a LoSS, NMAC, or MAC. The insight provided by ATC case study analysis not only provided insight for current ATC accident and incidents, but contributed to identifying potential UAS opportunities and divergence vulnerabilities in a future UAS-integrated NAS. For example, working memory failures, which did not appear as important to divergence prior to the ATC case study, provided insight on UAS vulnerabilities due to their atypical flight characteristics. In addition, the lack of or ambiguous observables leading to incorrect inferences in the comprehension process during the ATC case study highlighted the importance of explicit, unambiguous observables for aircraft intent, which may present vulnerabilities leading to divergence in an UAS-integrated NAS.

Following the ATC case study analysis, a future system was investigated to demonstrate the utility of the frameworks. Although a future UAS-integrated NAS was chosen for this demonstration, numerous areas within the ATC domain are applicable. For example, the concept of divergence could investigate future collision avoidance procedures to analyze the opportunities and divergence vulnerabilities coordinating state awareness and mitigation plans between conflicting aircraft and the controller to develop a means to mitigate the midair collision and reduce the potential for uncoordinated plans between the aircraft in the conflict and ATC. Also, divergence could be used to investigate coordination between aircraft and ATC for significant weather re-routing and optimized climb and descent profiles with increased satellite navigation procedures to promote consistent state awareness and coordinated plans.

11.4 Unmanned Aircraft Systems Investigation

To demonstrate the utility of the frameworks, an UAS-integrated NAS was investigated as an example of a near term large scale change to an existing system. To identify areas of investigation regarding a future UAS-integrated NAS, an ATC USA field study was conducted.

11.4.1 Air Traffic Control Unmanned Aircraft System Field Study

A field study of UAS-experienced air traffic controllers was conducted to identify controller divergence risk areas during mixed manned and unmanned operations in the NAS by performing focused interviews and observations of controllers managing UAS. The field study was conducted at nine military ATC facilities in the southwestern US and covered the majority of UAS operating locations for USAF group 4 and 5 UAS types. The holistic view afforded by the field study was used to identify potential emerging divergence issues for controllers and the results provided insight into the selection of UAS divergence investigation areas. These areas include the lack of onboard human perception, the potential for lost link, UAS flight characteristics including complex navigational paths, less structured routes, less predictable routes, static, long-duration flights, and performance characteristics, and various levels of control automation.

11.4.2 Implications for Future Unmanned Aircraft System National Airspace System Integration

The four divergence vulnerability areas determined important for UAS-integration were investigated to demonstrate the utility of the air traffic controller divergence cause and consequence framework and the air traffic controller cognitive process framework and to identify controller opportunities and divergence vulnerabilities in a future UAS-integrated NAS. Opportunities exist for increased controller awareness due to the ability for enhanced communication potential during UAS loss of traditional voice or data communications and less variation in aircraft intent during times of higher automation levels. However, many potential divergence vulnerabilities were apparent with UAS integration and potential design considerations were proposed to mitigate controller divergence with the integrations of UAS. UAS intent may be crucial yet more challenging for controller awareness due to the possibility of lost link, UAS flight operations, and various levels of control automation. Future UAS position is also important but may be more challenging to project due to UAS performance characteristics, flight operations, and various levels of control automation. In addition, once divergence occurs hazardous consequences may be more likely with UAS due to their inability to mitigate hazardous consequences themselves due to the lack of onboard human perception, lost link, or fully autonomous operations. Approaches and design considerations to mitigate controller divergence and its consequences prior to UAS-integration were also identified. Overall, this thesis highlights the importance of continued research of controller considerations as the NAS continues to evolve and become more advanced and crowded.

11.5 Future Work

As previously discussed, this research identified potential areas of opportunities and divergence vulnerabilities for UAS-integration in the NAS. However, once the UAS CONOPS become better defined, these areas will require further research to fully develop mitigations and understand their effectiveness to counter the causes and consequences of controller divergence.

The air traffic controller cognitive process framework could be enhanced further. For instance, the divergence assessment process within comprehension currently provides a binary output for divergence, either unknown or known as deterministic states. The certainty of the controller's state awareness is likely more complex than the deterministic decomposition shown here. This uncertainty may propagate to the decision and execution processes and future research is required to understand instances when levels of controller known divergence lead to actions such as elicitation of information, the commanding of a state, execution of conservative actions, waiting for increased awareness certainty, or other outcomes.

Although the frameworks developed were focused on air traffic controllers and the ATC system, the concept of divergence and the theory behind the frameworks as discussed in this thesis may also apply to other human-integrated systems when a human supervisor manages other dynamic agents requiring the perception, comprehension, and projection of their states. For instance, the divergence frameworks could be used in advanced traffic management of automobiles, trains, and ships. These domains correlate well to the divergence cause and consequence framework where a hazardous action by the human operator of an incorrect action or no action may lead to a potentially hazardous situation that could be mitigated by either the operator or the system. They also correlate well with the cognitive process framework where the human operator must perceive, comprehend, project, and store their state awareness and each could contribute to their divergence. Other applicable domains may include manufacturing, hospital, and power plant systems.

The divergence concept and frameworks could also be expanded to investigate multi-agent divergence. As seen in the ATC case study, many accident and incident cases included pilot and controllers both diverged, such as when pilots were diverged on their clearance and incorrectly informed controllers of their intent through verbal communications, contributing to controller divergence. Instances of UASO and controller divergence were also hypothesized and investigated in the UAS-integration study, such as the case with the lack of onboard human perception among UAS when both the UASO and controller may be diverged with respect to traffic or significant weather. It appears that some divergence can propagate from one agent to another while other divergence shows up in both human agents simultaneously. The manifestation of divergence, confounding effects of divergence, the propagation of divergence versus the trust of an agent, agents shared mental models and their relation to divergence, and the ability to overcome single agent divergence compared to a single agent's divergence corruption of other agents are interesting future research areas worth study. Multi-agent divergence appears important in both the ATC domain and also in other domains. For instance, multi-agent divergence could apply to aircraft collision avoidance scenarios, either manned or unmanned, where the consistency in both the state awareness of each human agent and also their plans for future mitigation of the hazardous consequence of a midair collision is desired.

The divergence concept and frameworks developed in this research can be used systematically to investigate opportunities and divergence vulnerabilities in human controllers to improve safety.

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Appendix A: Cues Associated with Unknown Divergence, Known Divergence, and Re-convergence

Unknown divergence cues:

- Controller testimony providing evidence of inconsistent state awareness versus system state
- Accident or incident occurring based on properly executed controller commands
- Unanticipated violation of a Federal Aviation Regulation (FAR), such as …
    - Loss of Standard Separation (LoSS) with another aircraft
    - Below minimum altitude with respect to terrain or obstacles
    - Runway incursion
- Unanticipated safety alerts, such as …
    - Short Term Conflict Alert (STCA) or Conflict Alert (CA)
    - Airport Surface Detection Equipment Model X (ASDE-X) alert
    - Airport Movement Area Safety System (AMASS) alert
    - Minimum Safe Altitude Warning (MSAW) alert
    - Traffic Collision Avoidance System (TCAS) Traffic Advisory (TA) or Resolution Advisory (RA) communicated to the controller by the pilot
- Pilot testimony of misunderstanding controller commands or procedures
- Controller or pilot miscommunication
- Pilot or other controller communication regarding a flight safety situation
- Non-conservative controller strategies or commands

Known divergence cues:

- Controller testimony referring to a known lack of knowledge or understanding of an aircraft state
- Controller signifying or communicating uncertainty of an aircraft state
- Controller testimony of an incongruent observable from expectation
- Controller confirming or eliciting communication to a pilot or another controller
- Controller strategy change

Re-convergence cues:

- Controller testimony to gaining state awareness or understanding
- Controller communication command to positively affect the air traffic situation after divergence
    - Following an automated safety alert (CA, ASDE-X, AMASS, MSAW)
    - Following the addition of another observable or observation
- Pilot communication answer to a clarifying controller communication question
- New observable perceived by the controller that would provide re-convergence

Appendix B: Divergence Causality Questions

Divergence causality questions were developed from literature and the cognitive process framework. This provides a hierarchical, backwards propagated series of questions to aid in determining the process failure, source, and mechanism of the divergence. Once a process or memory failure is determined, sub-questions attempt to identify the source of the process or memory failure. Again, once this is determined sub-questions attempt to identify the mechanism of the source.

Projection Process Failures

Working memory failure

- Was there evidence of a working memory failure of a future state during the event, which if accurately remembered may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Evidence of a working memory failure
    - Was there evidence of an attention failure causing a working memory failure during the event? (Yes, No)
        - Yes: Evidence of an attention failure causing a working memory failure
    - Was there evidence of stress causing a working memory failure during the event? (Yes, No)
        - Yes: Evidence of stress causing a working memory failure

Projection mental model failure

- Was there evidence of a mental simulation failure during the event, which if properly simulated may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Evidence of a mental simulation failure

Input failure

- Was there evidence of a lack of knowledge causing a mental simulation failure during the event? (Yes, No)
    - Yes: Evidence of a lack of knowledge causing the mental simulation failure
- Was there evidence of incorrect knowledge causing a mental simulation failure during the event? (Yes, No)
    - Yes: Evidence of incorrect knowledge causing the mental simulation failure
- Was there evidence of an attention failure causing a mental simulation failure during the event? (Yes, No)
    - Yes: Evidence of an attention failure causing a mental simulation failure
- Was there evidence of no current state assumption during the event, which if correctly assumed may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Current state divergence – see *Comprehension Process Failure*
- Was there evidence of an incorrect current state assumption causing a mental simulation failure during the event, which if correctly assumed may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Current state divergence – see *Comprehension Process Failure*

Comprehension Process Failures

Working Memory failure

- Was there evidence of a working memory failure of a current state during the event, which if accurately remembered may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Evidence of a working memory failure

    - Was there evidence of an attention failure causing a working memory failure during the event? (Yes, No)
        - Yes: Evidence of an attention failure causing a working memory failure
    - Was there evidence of stress causing a working memory failure during the event? (Yes, No)
        - Yes: Evidence of stress causing a working memory failure

Comprehension mental model failure

- Was there evidence of an integration failure during the event, which if accurately integrated may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Evidence of an integration failure
    - Was there evidence of a pattern-matching failure causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of a pattern-matching failure – see *Pattern-matching failure*
    - Was there evidence of an inference failure causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of an inference failure – see *Inference failure*
    - Was there evidence of an inaccurate observation causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of an inaccurate observation – see *Perception mental model failure*
    - Was there evidence of a lack of an observation causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of a lack of an observation – see *Perception failure*
    - Was there evidence of an ambiguous observation causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of an ambiguous observation causing an integration failure
    - Was there evidence of a lack of knowledge causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of a lack of knowledge causing the integration failure
    - Was there evidence of incorrect knowledge causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of incorrect knowledge causing the integration failure
    - Was there evidence of an attention failure causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of an attention failure causing an integration failure
    - Was there evidence of an expectation-driven comprehension bias causing an integration failure during the event? (Yes, No)
        - Yes: Evidence of an expectation-driven comprehension bias causing an integration failure
- Was there evidence of a pattern-matching failure during the event, which if accurately pattern-matched may have prevented divergence or promoted re-convergence? (Yes, No)
    - Yes: Evidence of a pattern-matching failure
    - Was there evidence of an inaccurate observation causing a pattern-matching failure during the event? (Yes, No)
        - Yes: Evidence of an inaccurate observation – see *Perception mental model failure*
    - Was there evidence of a lack of knowledge causing the pattern-matching failure during the event? (Yes, No)
        - Yes: Evidence of a lack of knowledge causing the pattern-matching failure

- Was there evidence of incorrect knowledge causing the pattern-matching failure during the event? (Yes, No)
  - Yes: Evidence of incorrect knowledge causing the pattern-matching failure
- Was there evidence of an attention failure causing a pattern-matching failure during the event? (Yes, No)
  - Yes: Evidence of an attention failure causing a pattern-matching failure
- Was there evidence of an expectation-driven comprehension bias causing a pattern-matching failure during the event? (Yes, No)
  - Yes: Evidence of an expectation-driven comprehension bias causing a pattern-matching failure

- Was there evidence of an inference failure during the event, which if accurately inferred may have prevented divergence or promoted re-convergence? (Yes, No)
  - Yes: Evidence of an inference failure
  - Was there evidence of a lack of an observation causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of a lack of an observation – see *Perception failure*
  - Was there evidence of an ambiguous observation causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of an ambiguous observation causing an inference failure
  - Was there evidence of a lack of knowledge causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of a lack of knowledge causing the inference failure
  - Was there evidence of incorrect knowledge causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of incorrect knowledge causing the inference failure
  - Was there evidence of an attention failure causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of an attention failure causing an inference failure
  - Was there evidence of an expectation-driven comprehension bias causing an inference failure during the event? (Yes, No)
    - Yes: Evidence of an expectation-driven comprehension bias causing an inference failure

Perception Process Failures

Perception mental model failure

- Was there evidence of an inaccurate observation during the event, which if observed may have prevented divergence or promoted re-convergence? (Yes, No)
  - Yes: Evidence of an inaccurate observation
  - Was there evidence of an inaccurate observable causing an inaccurate observation during the event? (Yes, No)
    - Yes: Evidence of an observable failure – see *Observable failure*
  - Was there evidence of a lack of knowledge causing the inaccurate observation during the event? (Yes, No)
    - Yes: Evidence of a lack of knowledge causing an inaccurate observation
  - Was there evidence of incorrect knowledge causing the inaccurate observation during the event? (Yes, No)
    - Yes: Evidence of incorrect knowledge causing an inaccurate observation
  - Was there evidence of a barrier to an observable causing the inaccurate observation during the event? (Yes, No)
    - Yes: Evidence of a barrier to an observable causing an inaccurate observation

- Was there evidence of an expectation-driven perception bias causing an inaccurate observation during the event? (Yes, No)
    - Yes: Evidence of expectation-driven search bias causing an inaccurate observation

Perception failure

- Was there evidence of a lack of perception during the event, which if perceived may have prevented divergence or promoted re-convergence? (Yes, No)
  - Yes: Evidence of a lack of perception
  - Was there evidence of an observable failure causing the lack of perception during the event?
    - Yes: Evidence of an observable failure – see *Observable failure*
  - Was there evidence of a barrier to an observable causing the lack of perception during the event? (Yes, No)
    - Yes: Evidence of a barrier to an observable causing a lack of perception
  - Was there evidence of an indiscriminate observable causing the lack of perception during the event? (Yes, No)
    - Yes: Evidence of an indiscriminate observable causing a lack of perception
  - Was there evidence of a poor information sampling strategy causing the lack of perception during the event? (Yes, No)
    - Yes: Evidence of poor information sampling strategy causing a lack of perception
  - Was there evidence of an expectation-driven search bias causing the lack of perception during the event? (Yes, No)
    - Yes: Evidence of expectation-driven search bias causing a lack of perception
  - Was there evidence of an expectation-driven attention bias causing the lack of perception during the event? (Yes, No)
    - Yes: Evidence of expectation-driven attention bias causing a lack of perception

Observable failure

- Was there evidence of a lack of an observable during the event, which if observed may have prevented divergence or promoted re-convergence? (Yes, No)
  - Yes: Evidence of a lack of an observable
  - Was there evidence of system design causing the lack of an observable during the event? (Yes, No)
    - Yes: Evidence of system design causing a lack of an observable
  - Was there evidence of a system failure causing the lack of an observable during the event? (Yes, No)
    - Yes: Evidence of a system failure causing a lack of an observable
  - Was there evidence of a system policy causing the lack of an observable during the event? (Yes, No)
    - Yes: Evidence of a system policy causing a lack of an observable
  - Was there evidence of system settings causing the lack of an observable during the event? (Yes, No)
    - Yes: Evidence of system settings causing a lack of an observable
- Was there evidence of an inaccurate observable during the event, which if accurate may have prevented divergence or promoted re-convergence? (Yes, No)
  - Yes: Evidence of an inaccurate observable
  - Was there evidence of human error causing the inaccurate observable during the event? (Yes, No)
    - Yes: Evidence of human error causing an inaccurate observable

- Was there evidence of a system malfunction causing the inaccurate observable during the event? (Yes, No)
    - Yes: Evidence of a system malfunction causing an inaccurate observable

Appendix C: Divergence Consequentiality Questions

- Was there evidence of additional human controller error during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Human controller error contribution to divergence
- Was there evidence of additional human controller error during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Human controller error contribution to consequentiality
- Was there evidence of pilot error during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Human pilot error contribution to divergence
- Was there evidence of pilot error during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Human pilot error contribution to consequentiality
- Was there evidence of another human controller error during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Human controller error contribution to divergence
- Was there evidence of another human controller error during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Human controller error contribution to consequentiality
- Was there evidence of an aircraft system error or failure during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Aircraft system error contribution to divergence
- Was there evidence of an aircraft system error or failure during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Aircraft system error contribution to consequentiality
- Was there evidence of an air traffic control system error or failure during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Air traffic control system error contribution to divergence
- Was there evidence of an air traffic control system error or failure during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Air traffic control system error contribution to consequentiality
- Was there evidence of an air traffic control procedure error during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Air traffic control procedure error contribution to divergence
- Was there evidence of an air traffic control procedure error during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Air traffic control procedure error contribution to consequentiality
- Was there evidence of environmental factors during the event, which if it was not present may have prevented divergence from occurring? (Yes, No)
  - Yes: Environmental factors contribution to divergence
- Was there evidence of environmental factors during the event, which if it was not present may have prevented a consequential situation from occurring? (Yes, No)
  - Yes: Environmental factors contribution to consequentiality

Appendix D: Case Summaries

Case Number: 1
NTSB Accident Number: OPS11IA246
Date: 20 January, 2011

Summary: Perception and comprehension failures caused the controller to become diverged in the coordinator's commanded altitude, which contributed to a NMAC.

Synopsis: A controller's unknown divergence contributed to a NMAC between a Boeing 777 (B-777) and two Boeing C-17s while transiting through New York ARTCC (ZNY) airspace. A coordinator told a controller working the B-777 to stop his aircraft at FL210 in its climb. While still on the line with that controller, the coordinator leaned toward another controller working two C-17s and told him to stop his flight at FL220 in their descent. This caused confusion and both the B-777 and the C-17s were told to level off at FL220. The B-777 responded to multiple TCAS RAs, resulting in a NMAC with both C-17 aircraft. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Factual Report, Investigation of NMAC Report, Controller Personnel Statements, and Crew Incident Report. Figure D-1 shows a close-up view of the radar track of the flights.

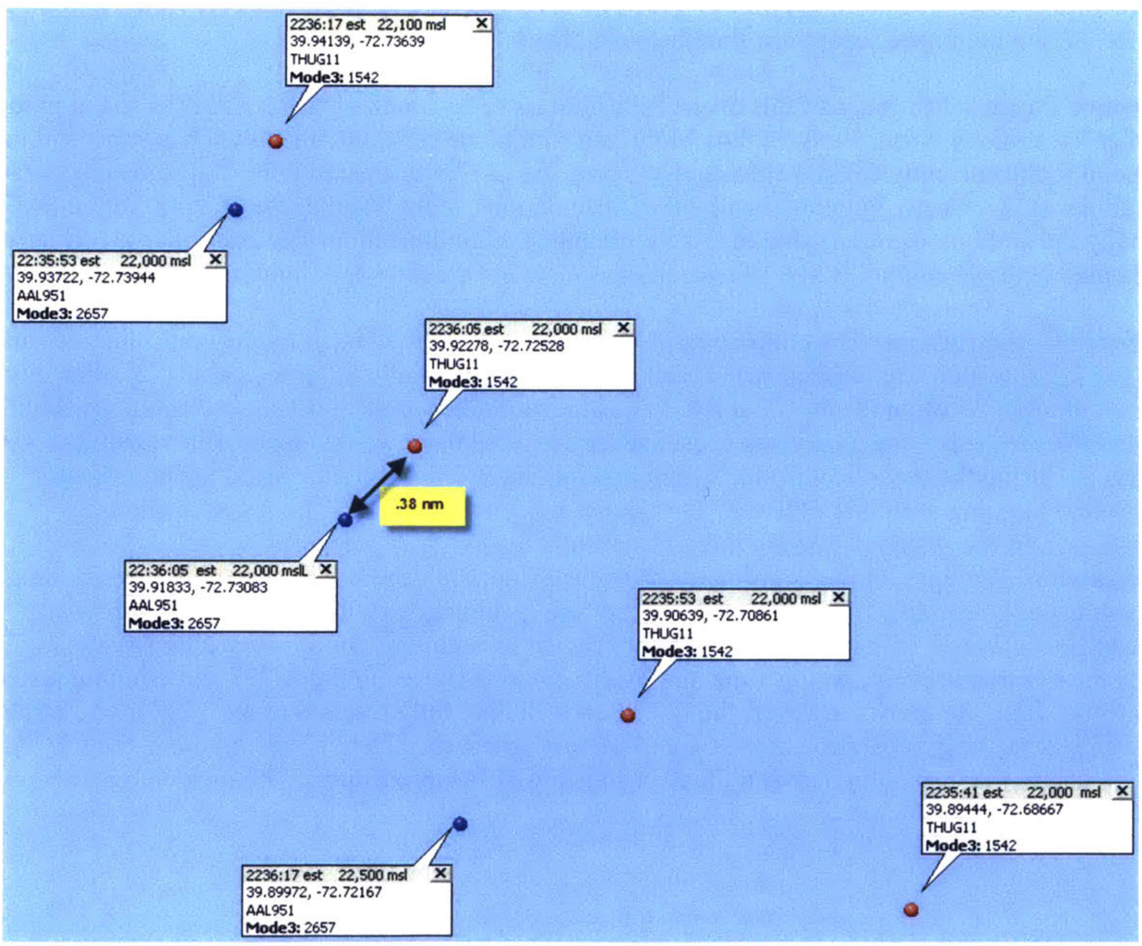

Figure D-1. Radar track of flights.

Table D-1. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Human error	Inaccurate observable	Perception	Coordinator's commanded altitude → Future aircraft separation	Incorrect (Clearing the B-777 to FL220)	Known divergence (normal visual scan) & Re-convergence (aural elicitation) / No recovery action	TCAS RA in B-777 (C-17 TCAS off)	NMAC
Ambiguous observable	Inference – ambiguous observable	Comprehension					
Unknown	Integration						

Divergence State: The controller experienced unknown divergence. Evidence of unknown divergence was based on controller testimony and miscommunication which became evident before the point of closest approach. According to testimony, the coordinator stated when the B-777 controller called him on the interphone, he "answered the call, told the R66 controller to stop AAL951's [B-777] climb at flight level 210, and then told the R86 controller to stop THUG11's [C-17] descent at flight level 220." However, the B-777 controller stated during testimony that "based on the altitude readout of THUG11's limited data block, and the rate of climb of AAL951, he thought he heard the D86 controller instruct AAL951 to maintain FL220." This demonstrated unknown divergence between the coordinator, who was instructing the B-777 controller to stop his aircraft at FL210, and the B-777 controller, who thought he wanted the B-777 to stop at FL220. The state of the B-777 controller's divergence appears to be the coordinator's commanded altitude of the B-777. The diverged state propagated to the future position state of the B-777 and the future separation state between the B-777 and C-17s.

Divergence Causes: The cause of this divergence appears to be due to multiple issues as stated in the controller's testimony. First, the C-17 data block had an altitude of 10,000 feet, which is supposed to correspond to the currently cleared altitude. However, the C-17 was cleared to FL220. This inaccurate observable was incorrectly integrated with other observations, including the rate of climb of the B-777 and finally the ambiguous observable of the coordinator's communication. The controller incorrectly inferred that the command to FL220 was for his B-777 rather the intended flight of C-17s.

Divergence Consequences: The consequential divergence manifested itself by the controller clearing the B-777 to FL220, which was an incorrect action and led to a potentially hazardous situation of an aircraft-to-aircraft conflict between the B-777 and C-17s as the controller of the C-17s also cleared his flight to FL220. However, before the hazardous consequence occurred there was evidence of a transition to known divergence. During the B-777 controller's normal scan, the B-777 controller asked the coordinator "Where are you going with that THUG?" This shows evidence of the B-777 controller eliciting information from the system, knowing that the current situation does not appear to reflect nominal future state separation. The reply of the coordinator provides evidence of the B-777 controller transitioning to re-convergence. In his reply, the coordinator stated "He is turning back to the left. I said stop that American [B-777] at 21." The transitions did not provide enough time for the controller to effectively mitigate the hazardous event. At this time, the TCAS RA was alerted in the B-777 and communicated to the controller from the crew. However, the B-777 crew did not fully respond to the TCAS RA, and lateral separation was the only separation at the time of closest approach. The C-17 did not have their TCAS turned on due to the formation between the two, standard USAF procedures. The incident resulted in a NMAC.

Case Number: 2
NTSB Accident Number: OPS11IA410
Date: 11 March, 2011

Summary: Perception and comprehension failures caused one controller to become diverged in an aircraft's transponder state, which allowed a perception failure to cause another controller to become diverged in the aircraft's existence, which contributed to three instances of LoSS.

Synopsis: Two separate controllers' instances of unknown divergences contributed to three instances of LoSS between a B-757 and three other aircraft on departure from Atlanta International Airport (ATL), Atlanta, Georgia. The B-757 departed without its transponder activated and the crew did not contact the Departure Controller (DC) for approximately 8 minutes after takeoff. The Local Controller (LC) did not notice the aircraft's transponder was not activated, which was one of the tasks of the LC in order to ensure the aircraft's data tag appeared for the DC. Next, the DC failed to recognize the B-757 in his airspace due in part to the lack of any data tag on the controller's TSD and no communication check-in from the aircraft's crew. During the approximate 8 minutes before communication and transponder were established, there was a LoSS between the B-757 and three different aircraft. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Factual Report, Operational Factors Factual Report, Flight Crew Written Statements, and Controller Personnel Statements.

Table D-2. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Distraction	Lack of Perception	Perception	Transponder on/off	Incorrect Action (passing communication to departure control)	Known divergence (departure controller)	None	N/A
No observation / Default value	Inference – guessing	Comprehension					
System Failure / Expectation-driven search and attention bias, Indiscriminate observable	Lack of observable / Lack of perception	Perception	Aircraft existence → Future aircraft separation	No Action (failed to mitigate LoSS)	Known divergence (FPS normal scan)	None	3x LoSS

LC Divergence State: The LC experienced unknown divergence. Evidence of unknown divergence was based on controller testimony. After the B-757 takeoff and final communication with the LC, the B-757 crew was instructed and replied that they would contact departure. Later, the Atlanta TRACON departure controller called him and asked about the B-757. The LC stated "that DAL2086 [B-757] had departed, but they would check into it." This communication between the LC and DC provided the transition from unknown to known divergence for the LC. There was no evidence of re-convergence during the incident. The state of divergence appears to be the current aircraft transponder state. According to the NTSB Synopsis, "Although local procedures require that Atlanta tower controller verify that departures have a radar data tag before transferring communications to departure controllers, the tower controllers did not do so."

LC Divergence Causes: The cause of the divergence appears to be due to a distraction caused by another radio call. The LC explained that a "pilot called him up and asked him about sandbags on the numbers of runway 27R." Later, the LC stated "the discussion about the sandbags interrupted his normal routine, which consisted of launching an aircraft, crossing the runway, clearing an aircraft to line up and wait, checking the departure for auto-acquisition, and watching for the turn in the right direction." This distraction led to poor information sampling away from his routine as described, and an inference failure guessing the state of the transponder, which may have been replaced with the default value of the transponder being nominal, signified by an incorrect action to clear him to the DC.

DC Divergence State: The DC experienced unknown divergence as well. Evidence of unknown divergence was based on controller testimony. The DC was unaware of the aircraft in his airspace until he noticed a "strip on DAL2086 come out, and because the pilot had not checked in on his frequency he called ATL tower to check on the flight's status." Although this served as the evidence for a transition to known divergence, this occurred approximately 4 minutes into the B-757's flight. The state of divergence appears to be the existence state of the B-757, which came later than usual because "He stated that normally when the strip came out it meant he should expect a rolling call [verbal notification from the tower that an aircraft was departing]." However, as stated before this did not occur for many minutes after the aircraft had departed.

DC Divergence Causes: The cause of this divergence was likely a combination of a lack of an observable by the B-757 crew due to a lack of a check-in radio call on the departure frequency and lack of perception of the B-757 on the TSD. The lack of perception on the TSD occurred likely due to a combination of expectation-driven search bias, expectation-driven attention bias, and an indiscriminate observable. The controller stated he "would have had a shot to see DAL2086 but I was looking away from that area and concentrating on Eagle Flight and other airplanes that I had on my frequency." Eagle flight had departed earlier on the wrong code and with an inoperative flight management system, and due to no expectation of an aircraft recently departing, the controller performed other duties. The B-757 crew had their own divergence and failed to turn their transponder on during ground operations. Next, the LC failed to accomplish their task of ensuring the data tag was placed on the TSD before handing the aircraft to departure control, as discussed in the first instance of divergence. Therefore, the lack of data tag on the TSD resulted in an indiscriminate observable. The NTSB stated "due to the large number of primary targets in that area" the controller failed to perceive the aircraft, signifying expectation-driven attention bias because he was not expecting an aircraft on departure. Even after understanding the need to find the B-757, the departure controller "conducted a futile search of the radar display for DAL2086's target," signifying the degree of the indiscriminate observable. However, after approximately 8 minutes of flight time, the departure controller re-converged due to communication between himself and the B-757 in combination of the transponder being turned on.

Divergence Consequences: During the incident, the potentially hazardous situation was determined to be the aircraft-to-aircraft conflict of the B-757 and the three various aircraft along its route of flight. The potentially hazardous situation was caused by the respective flight plans and the NAS structure, which does not necessarily guarantee separation without tactical controller intervention. However, the departure controller failed to mitigate the conflicting trajectories due to the two instances of divergence as described above. Luckily, this failure only resulted in three separate LoSS rather than more consequential outcomes before the departure controller experienced re-convergence. These three instances occurred for the same reasons and the data available did not provide definitive timelines to understand when they each occurred prior to re-convergence. However, although the controller did transition to re-convergence, this was likely after the three instances of LoSS.

Case Number: 3
NTSB Accident Number: OPS11IA476
Date: 13 April, 2011

Summary: Comprehension and projection failures caused a controller to become diverged in an aircraft's future position and another aircraft's pilot intent, which contributed to a NMAC.

Synopsis: A tower controller's two instances of unknown divergences contributed to a NMAC between a flight of two T-1s and a Raytheon-Beech King Air 300 (BE300) at Midland International Airport (MAF), Midland, Texas. The two T-1s entered the airport area on a left downwind approach to runway 28, while the BE300 entered the airport area on a wide right downwind to runway 28. The T-1s were executing an overhead pattern. After the conclusion of the overhead break by the T-1s, the second T-1 established itself in a trail formation of 1.4 nm. During this time, the BE300 was allowed to "continue for the runway" before being told "you'll be number 3 for the field following a flight of two Beech jets currently about a mile on the left base, report traffic in sight." However, the BE300 crew never acquired the second T-1 visually, yet turned to make a right base and final approach. This led to the second T-1 (call-sign Tone 97-2) and the BE300 flying within 0.3 nm of each other without visually identifying the other aircraft, resulting in a NMAC. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the Radar Tracks of the aircraft involved in the incident. Figure D-2 shows the radar tracks of the incident aircraft.

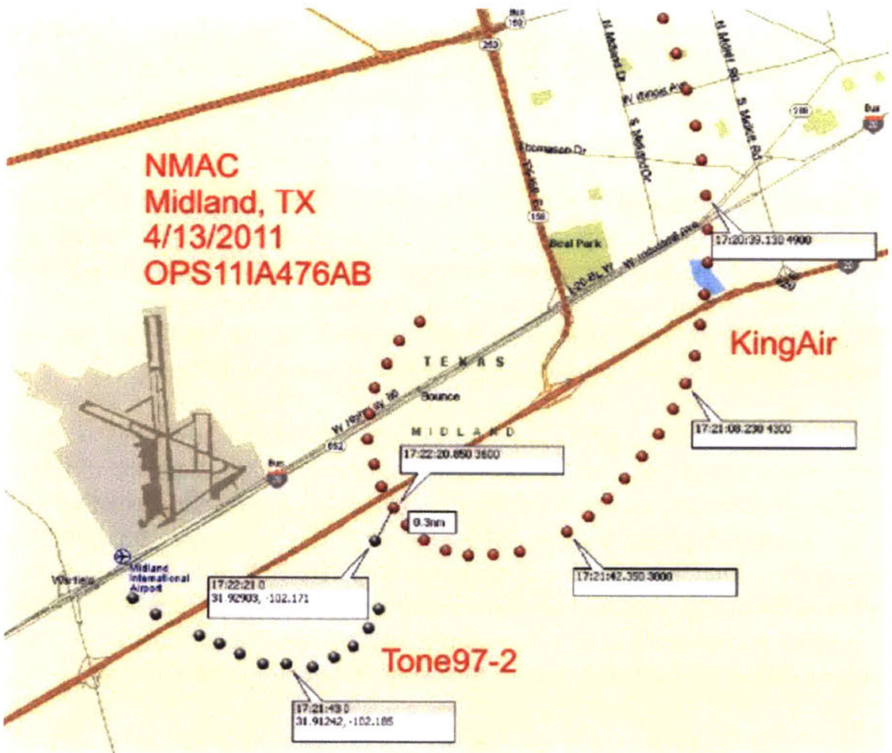

Figure D-2. Radar tracks of the incident aircraft.

Table D-3. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Default value	Incorrect knowledge	Projection	Future aircraft position → Future aircraft separation	Incorrect Action (communicating to BE300 to continue for the runway)	Re-convergence (normal scan VLO)	None	N/A
Lack of observable and Expectation-driven comprehension bias	Inference failure - guessing	Comprehension	Pilot intent → Future aircraft separation	No Action (failed to mitigate NMAC)	Re-convergence (normal scan VLO)	Pilot chose to breakout	NMAC

First Divergence: The tower controller experienced two instances of unknown divergence. Evidence of both instances of unknown divergence was based on controller testimony and the controller's action resulting in a NMAC. The first instance of unknown divergence related to the T-1 flight. According to NTSB testimony, the controller thought that if the pilots had actually executed the break at midfield, as he assumed they would, "it would have worked out." The first state of divergence appears to be the future aircraft position of the second T-1 in the flight, which propagated to the future aircraft separation between the second T-1 and the BE300. The cause of this divergence appears to be incorrect knowledge input to the mental model to project the aircraft's position into the future. According to testimony, the controller stated "he instructed the pilots to break at midfield, but the flight actually conducted their break further toward the departure end of the runway." In addition, the controller's instructor thought "the second T-1 was further in trail of the lead aircraft than would be normal for a standard formation flight" and "the pattern flown by the T-1s was wider than he expected. These various differences in the mental model used to project the future position contributed to the inaccurate future aircraft separation state between the second T-1 and the BE300.

The unknown divergence led the controller to communicate to the BE300 to "continue for the runway," an incorrect action that led to a potentially hazardous situation of an aircraft-to-aircraft conflict. However, there was evidence of re-convergence during the incident, based on the observables constantly perceived by the controller due to his normal scan technique. Based on this re-convergence, the controller commanded the BE300 that he would be 'number 3 for the field,' yet the BE300 crew turned base to final without visually acquiring second T-1, leading to another instance of divergence.

Second Divergence: During this divergence, the controller concluded that the "assumption bit us," referring to the controller's belief that the BE300 would not turn final until they had the second T-1 in sight. The second state of divergence appears to be the current pilot intent state of the BE300, which propagated to the future aircraft position of the BE300 and the future aircraft separation between the BE300 and the second T-1. The cause of this divergence was determined to be an incorrect inference in the comprehension process due to expectation bias. According to the local controller, "He did not expect the King Air to turn inbound toward the airport without having seen the second T-1." This divergence led to a projection of no violation of the future separation state between the two aircraft.

The unknown divergence led the controller to no action to mitigate the potentially hazardous situation of an aircraft-to-aircraft conflict. However, there was evidence of re-convergence based on the continued perceived observables of the aircraft tin the pattern. At the time of the BE300's turn toward final, the controller stated his "intent was to break one of the aircraft out to resequence it," showing evidence of re-convergence. However, the BE300 crew broke-out of the pattern themselves at this time. Yet there was no time to mitigate the situation before the BE300 pilot decided to break-out of the pattern on his own.

Case Number: 4
NTSB Accident Number: OPS11IA499
Date: 18 April, 2011

Summary: Projection failure caused a controller to become diverged in future aircraft separation, which contributed to a LoSS.

Synopsis: An approach controller's unknown divergences contributed to a LoSS between a B-737 and a Boeing C-17 on approach to Andrews AFB, Maryland. The controller vectored the C-17 onto base leg ahead of the B-737 to both join the localizer. The controller issued a wake turbulence advisory to the B-737, but the aircraft were 3.62 miles apart before being handed off to tower, with 5 miles wake turbulence separation minimum. Eventually, the B-737 performed a go-around and landed uneventfully. The incident resulted in a LoSS. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the Personnel Statements and Change to the FAA Order JO 7210.3.

Table D-4. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Mental Simulation	Projection	Future aircraft separation	Incorrect Action (poor vectors)	None	Pilot went around	LoSS

Divergence State: The approach controller experienced unknown divergence. Evidence of unknown divergence was based on controller testimony and the controller's action resulting in a LoSS. Although the aircraft were 3.62 miles apart with wake turbulence separation criteria of 5 miles, the controller professed that "until the debrief, he was not aware of any problems with the C17 and B737 arrival." The state of divergence appears to be the future aircraft separation between the B-737 and the heavy C-17.

Divergence Causes: The cause of this divergence is an apparent projection process failure. The controller vectored the aircraft less than the required 5-mile separation to 3.62 miles or less. The projection process failure appears to have been caused by a mental simulation failure, mainly due to no evidence of any corrupt inputs to the projection process itself.

Divergence Consequences: Based on unknown divergence, the controller continued to provide poor radar vectors, an incorrect action, to the aircraft creating a potentially hazardous situation of an aircraft-to-aircraft conflict. There was no evidence of a transition to known divergence or re-convergence during the incident. Then the aircraft were handed off to local control for landing. After attempting to continue the landing of both aircraft, the B-737 eventually executed a go-around and landed uneventfully, ending this incident in a LoSS rather than loss of aircraft control with an attempted landing.

Case Number: 5
NTSB Accident Number: OPS11IA8552
Date: 16 May, 2011

Summary: Working memory failure caused a controller to become diverged in an aircraft's existence state, contributing to a LoSS.

Synopsis: A tower controller's unknown divergences contributed to a LoSS between a Bombardier CRJ2 and an Embraer ERJ-145 at Chicago O'Hare International Airport (ORD). The CRJ2 was cleared to land by the North Local Controller (NLC) on runway 9R. Following this clearance, the Third Local Controller (3LC) issued the ERJ-145 clearance for takeoff on runway 32L, an intersecting runway to runway 9R. During the ERJ-145's takeoff roll, the FLM advised the NLC to command the CRJ2 to go-around. The incident resulted in a LoSS. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, the Operational Factors Group Chairman's Operations Report, Addendum 1 to the ATC Group Factual Report, and Errata to the ATC Group Factual Report. Figure D-3 shows the ASDE-X screen capture during the LoSS of the two aircraft.

Figure D-3. ASDE-X screen capture of CRJ2 approaching runway 32L on final approach to runway 9R.

Table D-5. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Unknown	Working memory	Aircraft existence → Future aircraft separation	Incorrect Action (takeoff clearance)	Known divergence (FLM communication) and Re-convergence (visual elicitation) / Recovery Action (Communication)	Pilot VLO from controller communication	LoSS

Divergence State: The approach controller experienced unknown divergence. Evidence of unknown divergence was based on controller and pilot testimony and the controller's action resulting in a LoSS. According to the NTSB, the 3LC "had seen SKW6958" (CRJ2), but "forgot about the arrival when he issued BTA6075 [ERJ-145] a take-off clearance from runway 32L," initiating the event for the LoSS. The state of the divergence appears to be the existence state of the CRJ2, which propagated to the future separation state between the two aircraft.

Divergence Causes: The cause of this divergence was likely due to a working memory failure following the controller's initial perception of the aircraft. According to controller testimony, the 3LC "scanned the final approach course for runway 9R to look for conflicting traffic and saw the approaching CRJ2. However, he then forgot about the arrival and cleared the ERJ-145 for takeoff." The working memory failure occurred for unknown reasons.

Divergence Consequences: Based on the controller's unknown divergence, he made an incorrect action of communicating a takeoff clearance to the ERJ-145 leading to a potentially hazardous situation of an aircraft-to-aircraft conflict. However, it appears the controller transitioned to known divergence and then re-convergence before the point of closest approach, potentially mitigating the hazardous consequences of the divergence. Evidence of known divergence is based on the controller's testimony in the NTSB investigation. According to the NTSB, after clearing the ERJ-145 for takeoff, the controller "heard the FLM yell, 'send that guy around,' referring to the runway 9R arrival." This observation was not previously noticed, and likely caused the controller to gather more information on the situation. Following the observation of the aircraft on final, the controller transitioned to re-convergence. According to the NTSB, the controller transmitted "aw [explicative]" one second before the NLC issued a go around for the CRJ2. In addition, according to pilot testimony, he "heard the controller key his mike and make a grunting UHH! sound that made me look up ... Instantly, I saw a blue United painted CRJ200 flying towards 32L." Although the subsequent communication to the ERJ-145 crew on takeoff roll was undecipherable, it appears to have caused the crew to visually acquire the CRJ2 on final and impact their trajectory in order to prevent a MAC or NMAC.

Case Number: 6
NTSB Accident Number: OPS11IA653
Date: 14 June, 2011

Summary: Comprehension and working memory failures caused one controller to become diverged in a pilot's intent and current minimum vectoring altitude while a working memory failure caused another controller to become diverged in their control responsibility, contributing to a NMAC.

Synopsis: A tower controller and an approach controller had apparent instances of unknown divergence, which contributed to a NMAC between a Raytheon-Beech 1900 and a Piper Navajo approximately 3.5 nm west of Fairbanks International Airport, AK. The Beech 1900 was northeast bound toward the airport descending to enter the traffic pattern, while the Piper had just departed and was climbing on a westbound heading. Although both aircraft were operating under VFR, the Beech 1900 was receiving ATC services from approach control while the Piper was receiving ATC services from the tower controller. The tower controller noted the potential conflict between the two aircraft and issued three traffic advisories to the Piper, along with an altitude; however, the Piper never gained visual contact of the Beech 1900. The Beech 1900 received no advisory due to the approach controller incorrectly assuming the Beech had transferred communication to tower. The incident resulted in a NMAC, with the Beech 1900 crew attaining visual contact of the Piper and maneuvering to avoid. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, and NTSB Data Summary.

Table D-6. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Expectation-driven comprehension bias	Integration and Inference	Comprehension	Pilot intent → Future aircraft separation	Incorrect Action (control commands)	None	Pilot VLO	NMAC
Unknown	Unknown	Working memory	Current MVA → Future aircraft separation	Incorrect action (vector below MVA)	None	Pilot VLO	LoSS
Unknown	Attention	Working memory	Control responsibility → Future aircraft separation	No action (failed to mitigate)	None	Pilot VLO	NMAC

Tower controller: The tower controller experienced two instances of unknown divergence. Evidence of the first instance of unknown divergence was based on NTSB investigation findings, controller testimony, and an unanticipated NMAC. According to controller testimony, she "had not noticed a conflict alert involving the two aircraft on the radar display" and she "did not immediately recognize the event as a possible operational error … until then, the local controller had not realized how close together the aircraft had been." Evidence of the second instance of unknown divergence was based solely on the NTSB investigation findings. During the incident there was a violation of MVA that went unnoticed by any of the controllers. There was no evidence of a transition to known divergence or re-convergence for either instance of unknown divergence.

It appears the first state of divergence for the tower controller during this incident was the pilot intent state in the Beech 1900, which propagated to the future position state of the Beech 1900 and future separation state. According to the NTSB Full Narrative, in order to provide vertical separation between the two aircraft, the tower controller "instructed the pilot to remain at or below 2,000 feet." The CIC thought the Beech "had been level at 2,500 feet for quite a while and that was why the local controller gave ERR12K [Piper] an altitude restriction to maintain at or below 2,000 feet." However, the NMAC occurred with the Beech 1900 flying under the Piper, who was level at 2,000 feet. The cause of the first instance of divergence was likely a failed comprehension process due to a failure of integrating various observations and inferring an ambiguous observation. The continued flight of the Beech 1900 at 2,500 feet and the controller's assumption "that the approach controller was retaining the aircraft to provide separation" led to expectation bias that the aircraft was going to continue at 2,500 feet until the point of closest approach. This divergence led to incorrect actions of control commands leading to a potentially hazardous situation of an aircraft-to-aircraft conflict. The Piper received no safety alert due to the indiscriminate observable of the Conflict Alert (CA), which the controller said she didn't hear until after the incident. However, the Beech 1900 crew's VLO mitigated the incident to a NMAC.

The second state of divergence for the tower controller appears to be the current MVA. The cause of this divergence was a working memory failure of the MVA. This led to an incorrect action of a vector below MVA and a potentially hazardous situation of an aircraft-to-terrain conflict. However, this was mitigated due to pilot VLO.

Approach controller: It appears the state of divergence for the approach controller during this incident was the control responsibility state for the Beech 1900, which led to no control services provided to it. The cause of the divergence was likely a working memory failure of the current state assumption. According to the NTSB Full Narrative, "He believed that he had transferred communications on WAV401 [Beech 1900] to the tower" and further stated "that it never occurred to him that WAV401 might still have been on his frequency." Contributing to this working memory failure may have been an attention issue, as the controller stated at the time of the incident, "he was also occupied with control action involving a Stationair and another aircraft elsewhere in the sector." Finally, contributing to the working memory failure may have been a lack of an observable due to system design and organizational decisions. The controller stated "he did not use any memory aids for indicating that communication had been transferred on the aircraft because there was no good way to do that using the Automated Radar Terminal System (ARTS)." In addition, the radar controllers in the facility used flight strips for IFR inbounds and all departures, but not for VFR inbounds.

Case Number: 7
NTSB Accident Number: OPS11IA673
Date: 19 June, 2011

Summary: Projection failure caused a controller to become diverged in an aircraft's future position state, contributing to a NMAC.

Synopsis: A tower controller's unknown divergences contributed to a NMAC between a C-172 and an ERJ-145 at Gulfport-Biloxi International Airport (GPT). The C-172 was cleared for takeoff at the intersection of runway 18 and taxiway A by the local controller. Sixteen seconds later, the ERJ-145 called ready for takeoff runway 14 and was subsequently cleared. The departure flight path of runway 18 intersected with the departure flight path of runway 14. The incident resulted in a NMAC. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Pilot Statements, Preliminary Operational Error/Deviation Investigation Report, and the Airport Diagram. Figure D-4 shows the airport diagram.

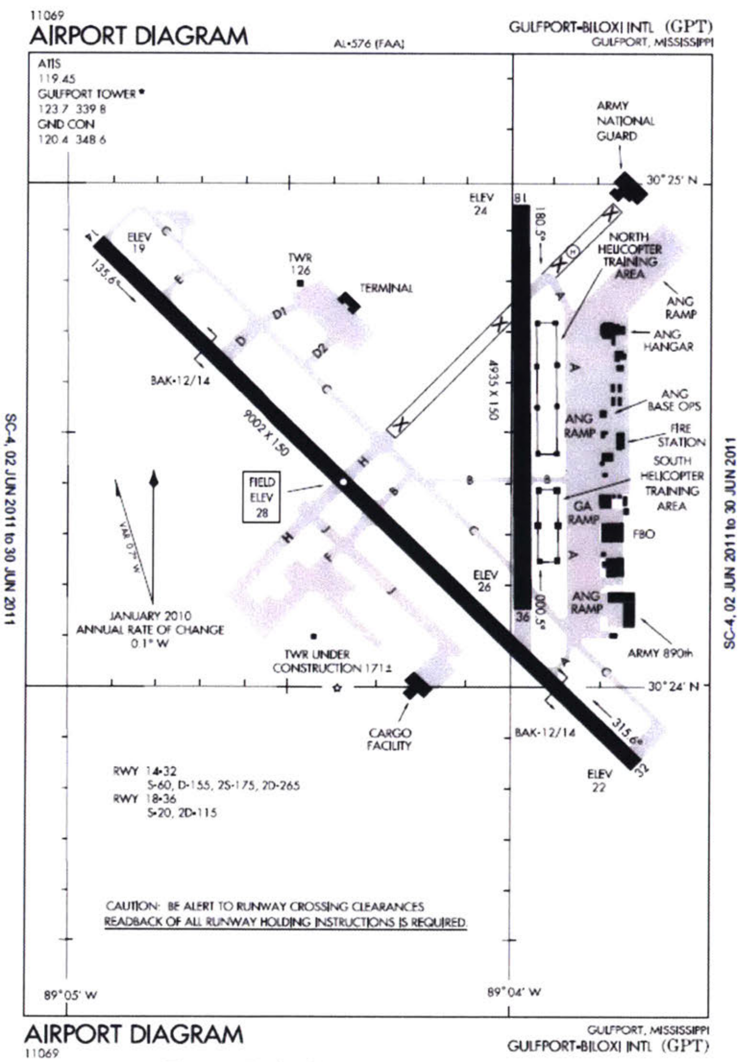

Figure D-4. GPT Airport Diagram.

Table D-7. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Default value	Incorrect knowledge	Projection	Future aircraft position → Future aircraft separation	Incorrect Action (takeoff clearance)	None	None	NMAC

Divergence States: The tower controller experienced unknown divergence. Evidence of unknown divergence was based on controller and pilot testimony and the controller's actions resulting in a NMAC. According to the NTSB report, after the NMAC the ERJ-145 crew asked about the C-172 traffic. The controller "was confused and could not figure out what the E145 was talking about. Mr. Beck [controller] considered it inconceivable that the Cessna departing runway 18 could have conflicted with the E145 off of runway 14." In fact, the controller "did not observe the event and was not aware that an OE [Operational Error] had occurred." The state of the divergence appears to be the future position of the C-172, which propagated to the future separation between the two aircraft.

Divergence Causes: The cause of this divergence was likely due to incorrect knowledge input to the mental model. Based on controller testimony, when the controller scanned the airport prior to clearing the ERJ-145 for takeoff, he said he noted the C-172 on taxiway A not yet moving. According to the NTSB, he anticipated "the Cessna could take 3-5 minutes to get airborne, from previous experience working with that specific aircraft."

Divergence Consequences: Thinking the future position of the C-172 would not conflict with the future position of the ERJ-145, he cleared the ERJ-145 for takeoff. This action was a violation of FAA Order 7110.65, which requires the preceding aircraft to be past the intersection of the two runways or flight paths before the other aircraft begins its takeoff roll, as well as a hazardous action (incorrect action) leading to a potentially hazardous situation of an aircraft-to-aircraft conflict. After the hazardous event, the controller could have mitigated the consequences by monitoring both aircraft as they approached the runways, but he missed these observations for numerous reasons. First, the controller likely had expectation bias based on his previous projection that the aircraft would not be in conflict. According to testimony, the controller thought the conflict was 'inconceivable' based on his previous experience with the Cessna. Second, the controller likely had poor information sampling and attention allocation. According to the NTSB, the controller "was assisting the approach controller with a flight progress issue at the flight data input/output terminal and did not observe the two aircraft depart." Also, the Flight Line Manager stated the incident occurred because the controller "was not paying attention." Another controller in the tower cab stated the incident controller "did not demonstrate good scanning technique or situational awareness." After failing to monitor the aircraft takeoffs, another controller in the tower cab stated "you've got two rolling," but this observation was missed by the incident controller for unknown reasons. Therefore, there was no evidence of a transition to known divergence or re-convergence during the incident. Also, the system failed to mitigate the incident, neither pilot saw each other until the point of closest approach; therefore, the incident was not a MAC due only to the initial geometry, not mitigations within the system.

Case Number: 8
NTSB Accident Number: OPS11IA819
Date: 8 August, 2011

Summary: Perception failure caused a controller to become diverged in an aircraft's existence, contributing to a NMAC.

Synopsis: A tower controller's apparent unknown divergences contributed to a NMAC between an ERJ-135 Chautauqua Airlines flight 5021 (CHQ5021) and an ERJ-145 Trans State Airlines flight 3367 (LOF3367) at Chicago O'Hare International Airport (ORD). CHQ5021 was cleared to land by the North Local Controller (NLC) on runway 9R. Shortly following this clearance, the Third Local Controller (3LC) issued LOF3367 clearance for takeoff on runway 32L, an intersecting runway to runway 9R. During LOF3367's takeoff roll, the 3LC advised the NLC to command CHQ5021 to go-around while he (3LC) provided a traffic alert to LOF3367 regarding CHQ5021 during their takeoff. The incident resulted in a NMAC. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report and the Operational Factors Group Chairman's Operations Report. Figure D-5 shows the ASDE-X screen capture during the point of closest approach between the two aircraft.

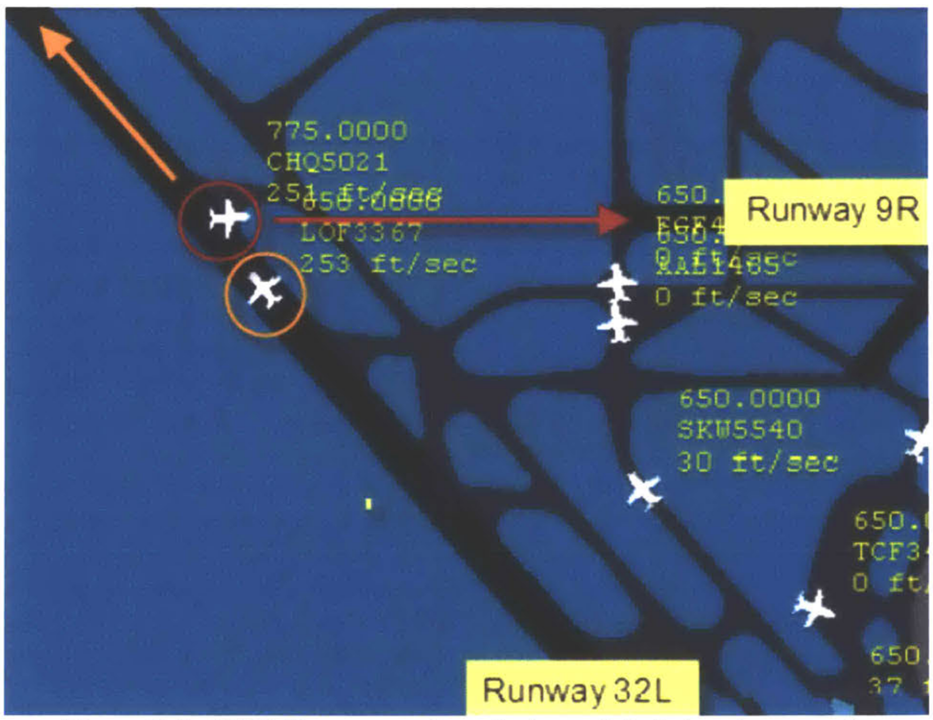

Figure D-5. ASDE-X screen capture during point of closest approach.

Table D-8. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Attention Allocation Issue (Stress)	Lack of Perception	Perception	Aircraft existence → Future aircraft separation	Incorrect Action (takeoff clearance)	Known divergence (normal scan) & Re-convergence (elicitation)	VLO (ATC communication)	NMAC

Divergence State: The tower controller experienced unknown divergence. Evidence of unknown divergence was based on controller and pilot testimony and the controller's action resulting in a NMAC.

According to the NTSB, the 3LC did not recall seeing the Chautauqua aircraft on final when he cleared LOF3367 for takeoff, initiating the event for the NMAC. The state of the divergence appears to be the existence state of CHQ5021, which propagated to the future separation state between the two aircraft.

Divergence Causes: The cause of this divergence was likely due to a lack of perception regarding CHQ5021 during the controller's normal scan for departures. According to controller testimony, the 3LC "did not recall seeing the Chautauqua data tag on the radar display" nor "recall where Chautauqua was at that [the time of his departure scan] time." This missed observation was likely due to multiple attention issues at the time, namely the stress caused by the increased complexity and numerous distractions. First, during controller testimony the 3LC stated "that the recipe for his mistake included the complexity of working the triple approaches, the north satellite coordination light coming on, and the two heavy airplanes on runway 10." The tower was under Plan X at the time of the incident, which increased complexity and coordination/communication requirements inside the tower cab. In addition, there had been much coordination for two heavy departures at the time of the incident, possibly causing a distraction for the controllers. In fact, the Local Assist and Local Assist Monitor both speculated that this could have been a distraction for the 3LC.

Divergence Consequences: Following divergence, the tower controller cleared LOF3367 for takeoff (incorrect action) creating an aircraft-to-aircraft conflict (potentially hazardous situation). However, it appears the controller transitioned to known divergence then re-convergence before the point of closest approach, potentially mitigating the hazardous consequences of the original divergence. Evidence of known divergence is based on the controller's testimony in the NTSB investigation. According to the NTSB, after clearing LOF3367 for takeoff, the controller "was going to turn the departure eastbound when the aircraft reached 3100 feet. When he did his departure scan, he saw Chautauqua coming in on 9R." Following this transition to known divergence, since the existence of CHQ5021 was likely divergent before but not after this observation, led the controller to assess the position of LOF3367 to determine future separation between the two aircraft. This observation led to a transition to re-convergence after another observation. According to the NTSB, the controller "then saw that Trans States was rolling." This re-convergence led to the appropriate decision and execution to remedy the situation, by telling "the NLC controller to send Chautauqua around, and … issued a traffic alert to the Trans States flight." The crews of both aircraft were able to visually acquire each other, resulting in a NMAC rather than a MAC.

Case Number: 9
NTSB Accident Number: OPS12IA041
Date: 14 October, 2011

Summary: Perception failure caused controller divergence in the pilot's intent, contributing to a LoSS.

Synopsis: A tower controller's unknown divergences contributed to a LoSS between two C-172s at the Daytona Beach International Airport (DAB), Daytona Beach, FL. Riddle 488 (R488) was cleared for takeoff on runway 7L, but mistakenly departed runway 25R while Riddle 551 (R551) was turning base to final approach for runway 7L, opposite direction of R488. The incident took place in night VMC. During the incident, the controller failed to monitor the takeoff of R488 or provide safety alerts when he recognized the impending LoSS. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Controller Personnel Statements, Pilot Deviation Report, and Pilot Statements.

Table D-9. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Human error	Inaccurate observable	Perception	Pilot intent → Future aircraft separation	No Action (to mitigate takeoff)	Known divergence (CA activation) / No recovery action	Pilot VLO	LoSS
Observable barrier	Inaccurate observation						
Expectation-driven perception bias							

Divergence States: The tower controller experienced unknown divergence. Evidence of unknown divergence was based on the NTSB findings, controller and pilot testimony, and an unanticipated CA. According to the NTSB, when scanning the runway for the R488's departure, the controller stated "he saw R488's lights moving and thought everything was good." According to R488 pilot testimony, "The other riddle plane called tower and said he noticed me. Tower didn't notice until he did so." The state of the unknown divergence was determined to be the pilot intent state of R488, which propagated to the future position state of R488 and future separation state between R488 and R551.

Divergence Causes: The cause of divergence was a perception failure, while the source was an inaccurate observable of the pilot's clearance read-back and an inaccurate observation while the aircraft was taking the runway for takeoff. The inaccurate observation was likely caused by the difficulty in observing the aircraft at night in combination with expectation-driven perception bias from the clearance acknowledgement. According to the NTSB, the controller said "his cue to determine if an airplane was positioned correctly included looking to the left (toward runway 7L) and anticipating that the airplane was going to depart in the right direction. He saw R488's lights moving and thought everything was good."

Divergence Consequences: Diverged, the controller took no action (hazardous action) to mitigate the pilot's wrong direction takeoff, leading to a potentially hazardous situation of an aircraft-to-aircraft conflict. However, there was evidence of a transition to known divergence. According to the NTSB, "When the CA activated on this incident, Mr. Koteff's [controller] first thought to himself was, 'is she going the right way?' He then asked the CIC [Controller-In-Charge] if that, '...looked right' to him (indicating R488's data tag on the radar display) just to get a second opinion. Mr. Koteff said, '...my brain could not comprehend what my eyes were seeing'." Yet there appears to be no evidence of complete re-convergence before the point of closest approach between the two aircraft. The NTSB said "It took him [controller] about 10 seconds to realize that R488 had departed the wrong way. By that time R551 had reported that an airplane had over flown him." After the initial divergence, the controller likely missed additional observations of the aircraft on takeoff and departure that could have resulted in re-convergence. According to the CIC, the controller "needed to become more focused and be more vigilant" and felt that the controller's "attention was split in too many directions at that time." Proper VLO by the pilots allowed for this incident to result in a LoSS rather than a NMAC or MAC.

Case Number: 10
NTSB Accident Number: OPS12IA122
Date: 3 November, 2011

Summary: Projection and working memory failures caused one controller to become diverged in two aircraft's future separation and the minimum vectoring altitude, while a projection failure caused another controller to become diverged in two aircraft's future separation, contributing to two separate LoSS.

Synopsis: Two different controller's unknown divergences contributed to two different LoSS between three aircraft and vectors below MVA at Kahului Airport while on approach to final. Hawaiian Air Lines flight 126 (HAL126) was on visual approach runway 2 and American Air Lines flight 253 (AAL253) was cleared the RNAV Z runway 2 approach. The controller's intent was for AAL253 to follow HAL126 on the approach, standard separation was lost and the AAL253 crew requested a turn in order to visually follow the aircraft. During the subsequent vectoring, AAL253 was below MVA. Finally, United Air Lines flight 575 (UAL575) was vectored behind AAL253 on the next approach attempt, but the relief controller failed to ensure adequate separation between these two aircraft while UAL575 overtook AAL253. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report and a MVA Chart. Figure D-6 shows the radar plots of all three aircraft involved in the incident.

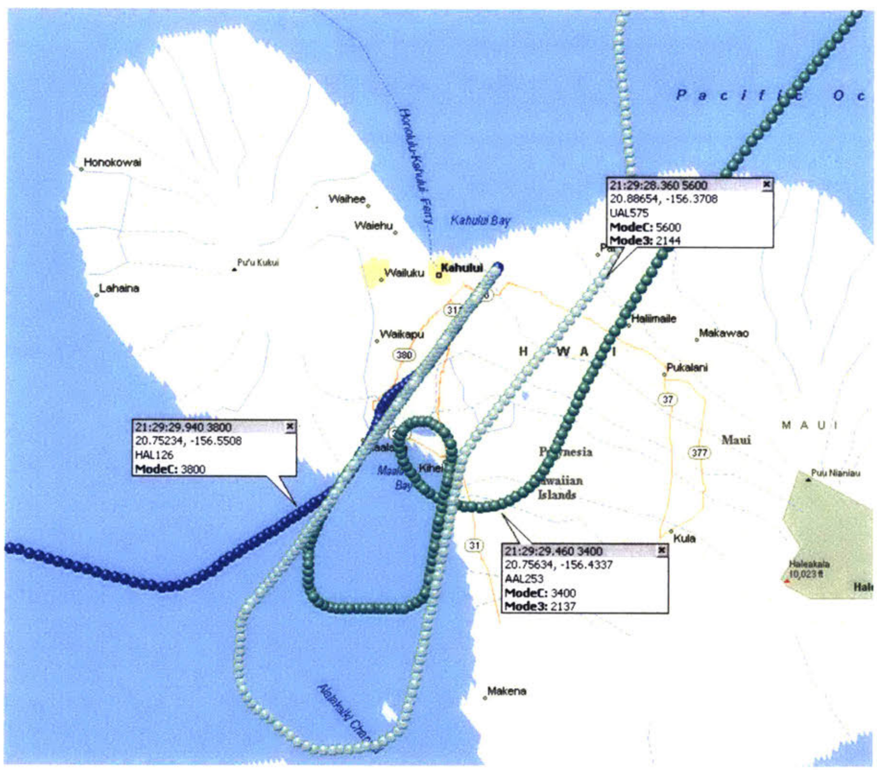

Figure D-6. Overview of the radar plots of all three aircraft involved.

Table D-10. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Mental Simulation	Projection	Future aircraft separation	Incorrect (AAL253 cleared approach)	Re-convergence (TSD) / Recovery action (vector)	None	LoSS
Stress	Working Memory	Comprehension	Minimum vectoring altitude → Future aircraft separation	Incorrect (Vectored off approach)	None	None	LoSS
Unknown	Mental Simulation	Projection	Future aircraft separation	No action (to mitigate)	None	None	LoSS

Divergence States: The first approach controller experienced unknown divergence. Evidence of the first instance of unknown divergence was based on the controller's testimony. During the approach, the On-the-Job-Training-Instructor (OJTI), who took over from the Developmental Controller, testified "As the aircraft approached the second fix, he determined that the spacing would be sufficient." However, as AAL253 was approaching the next fix on the approach, "he determined that the spacing was not going to be sufficient." The state of the unknown divergence was the future separation state between HAL126 and AAL253.

Divergence Causes: The cause of this divergence was likely a projection process failure. According to the NTSB ATC Group Factual Report, the OJTI felt that "when HAL126 slowed in response to the compression with UAL565, it had created a compression with AAL253 on the RNAV Z approach." The controller was not aware of this compression until the LoSS had occurred. According to the NTSB, a contributing factor was the inadequate training provided to controllers regarding the RNAV approach. According to the controller, he "did not remember seeing this type of sequencing situation covered in the training."

Divergence Consequences: Once diverged, the controller cleared AAL253 for the approach (hazardous action – incorrect action), creating an aircraft-to-aircraft conflict. The controllers stated they didn't hear any CA during the incident. However, the controller re-converged during the incident based on his testimony as stated above. Following re-convergence, the controller gave AAL253 a vector to 180 degrees, experiencing unknown divergence a second time.

Divergence state: Evidence of the second instance of unknown divergence was based on controller testimony and the violation determined by the NTSB. As the controller was giving AAL253 a vector to 180 degrees, he was unaware of the MVA at that location. According to the NTSB, the MVA at the location where AAL253 was initially turned was 4600 feet, with the next segment at 2700 feet. According to the NTSB, the controller "had not remembered that the MVA in the subsequent segment had gone up to 2700 feet until he had been relieved from the position." The state of the divergence appears to be the current MVA propagating to a future aircraft separation as described above.

Divergence causes: Based on analysis, it appears the current MVA state diverged due to a working memory failure. According to the NTSB, the controller "reverted to the previous MVA altitude of 2500 feet due to the stress of the situation." This stress contributed to the apparent working memory failure of the current MVA state.

Divergence consequences: Once diverged, the controller provided a vector below MVA (hazardous action – incorrect action) contributing to an aircraft-to-terrain conflict (potentially hazardous situation). There was no evidence of a transition to known divergence or re-convergence during the incident. The controller's next command to the aircraft was a climb above the MVA, rendering the state no longer task relevant. After these two instances of divergence, the controllers were relieved of duty and another controller took over approach control.

Divergence state: However, this controller experienced unknown divergence as well. Evidence of unknown divergence was based on the NTSB findings and controller testimony. According to the NTSB, the controller "continued working the position and did not know about the loss of separation involving AAL253 and UAL575 until after he was relieved." The state of divergence appears to be the future separation state between AAL253 and UAL575.

Divergence causes: This divergence appears to be caused by a failed projection process, specifically a mental simulation failure. According to testimony, the controller received a position relief briefing where the previous controller "indicated AAL253 had been cleared for the localizer approach, and UAL575 had been cleared for the ILS approach with a 170-knot speed restriction. Mr. Olson observed UAL575 at 210 knots and slowing. He last saw UAL575 at 170 knots and did not notice the compression occurring on final."

Divergence consequences: Once diverged, the controller failed to mitigate the aircraft-to-aircraft conflict (potentially hazardous situation) with a control action (hazardous action – no action). There is no evidence of known divergence or re-convergence prior to the closest point of approach between the two aircraft. This occurred based on the previous clearances from the previous controller. However, the divergence that occurred above failed to resolve the conflict leading to a LoSS

Case Number: 11
NTSB Accident Number: OPS12IA167
Date: 1 December, 2011

Summary: Perception failure caused the controller to become diverged in the pilot's intent state, which contributed to a NMAC.

Synopsis: A tower controller's unknown divergence contributed to a NMAC between a B-737 and a Learjet 45(LJ45) at Midway International Airport (MDW). The B-737 was cleared to cross runway 31R immediately after the LJ45 was cleared for takeoff on the same runway. During the event, the LJ45 was cleared for takeoff on runway 31R. However, after landing on runway 31C, the B-737 was instructed to cross runway 31R immediately after the LJ45 takeoff clearance was given. The first officer of the B737 saw the LJ45 on takeoff and commanded the captain of the B-737 to stop. The B-737 was across the hold-short line, but the aircraft closest proximity during the event was 287 feet lateral and 62 feet vertical spacing. No ATC commands or instructions were given during the incident to prevent it from occurring. Although the airport was equipped with ASDE-X, the system did not activate during the incident. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Crew Statements, and Final Operational Error/Deviation Report. Figure D-7 shows the radar data at the time of the LJ45's rotation.

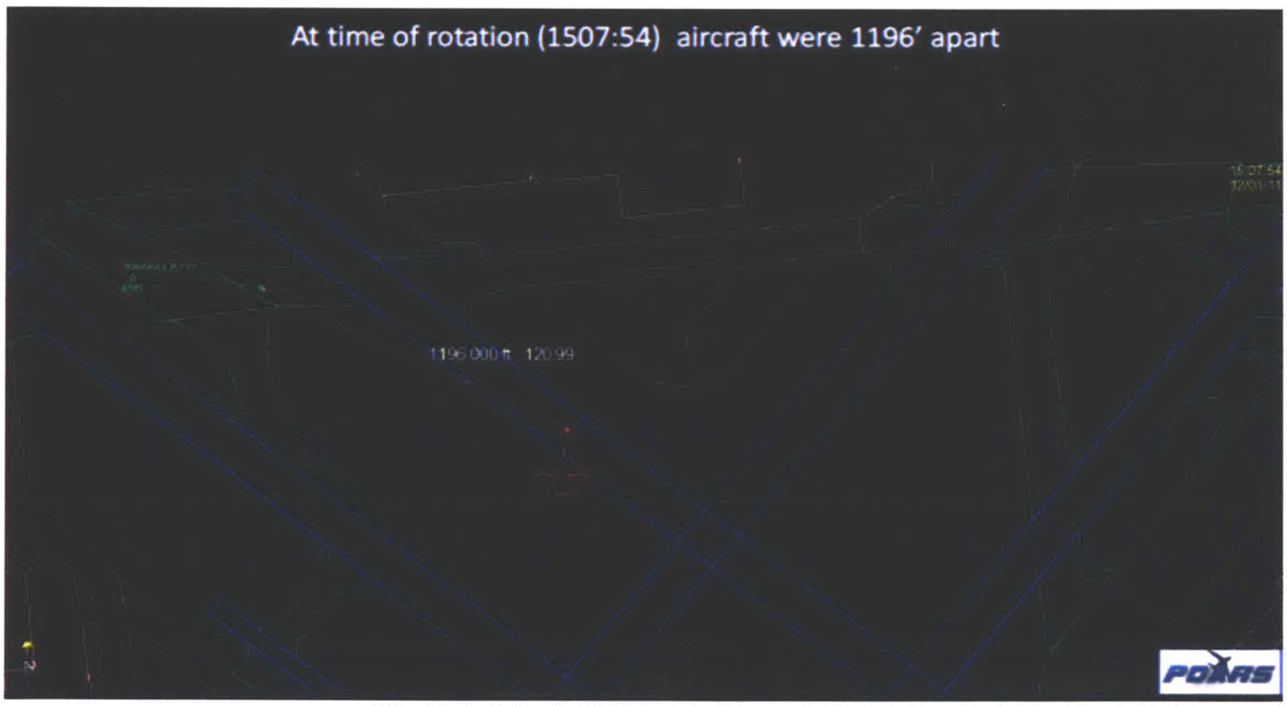

Figure D-7. Radar data at the time of rotation.

Table D-11. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Expectation-driven perception bias & attention	Inaccurate observation	Perception	Pilot intent → Future aircraft separation	Incorrect (Clearing LJ45 for takeoff)	Known divergence (assist communication)	Crew VLO	NMAC

Divergence State: The tower controller experienced unknown divergence. Evidence of unknown divergence was based on NTSB investigation findings and controller and pilot testimony. According to the NTSB, at 09:07:17, the local controller instructed GAJ17 [LJ45] to fly heading 220 degrees and cleated the flight for takeoff, following immediately with directions to SWA844 [B737] to, '...turn right, cross runway 31R, contact ground'." The controller stated in testimony that "He had intended to have SWA844 [B737] exit to the right near the end of runway 31C and hold short of runway 31R." and "He said he did not remember giving the crossing instruction." The controller's state of divergence was likely the pilot's intent in the B-737 aircraft. The controller said "he believed he had instructed SWA844 [B737] to hold short of runway 31R," which in actuality he had told the B-737 to cross runway 31R. This divergence propagated to a divergence in the future position of the B-737, which propagated to a divergence in the future separation state of the two aircraft.

Divergence Causes: Based on analysis, the divergence was initiated based on an action 'slip' of the controller when instructing the B-737 to cross runway 31R. As stated earlier, the controller's intention was to have the B-737 hold short. This caused a change in the actual system state. However, the controller's state assumption did not change and therefore unknown divergence occurred. This occurred due to the inaccurate observation of the pilot's read back of the runway crossing clearance. This inaccurate observation was due to expectation-driven perception bias in part. As stated earlier, the controller state "he believed he had instructed SWA844 to hold short of runway 31R." In addition, attention played a part in divergence, possibly due to the stress of the VIP aircraft inbound along with the high workload. The controller described the activity at the time "as busier than normal."

Divergence Consequences: Following divergence, the controller provided an incorrect action (hazardous action) by clearing the LJ45 for takeoff, producing an aircraft-to-aircraft conflict (potentially hazardous situation). The controller potentially experienced known divergence immediately before the point of closest approach between the two aircraft. During the incident, both the local controller assist and the front line manager asked if the B737 was stopping while it was approaching the intersection of runway 31R due to its high rate of speed. According to the local controller's testimony, "He heard Mr. Voss [front line manager] ask if an aircraft was holding short" but "was unsure about which aircraft Mr. Voss was referring to." However, ATC did not take any actions to resolve the conflict between the two aircraft. The observable barrier of the geometry of the tower cab and other controllers in the room at the time prevented the controller from visually observing the B737 during the incident, which may have resulted in an accurate observation later in the incident. In addition, the ASDE-X alarm never alerted during the incident. However, the crew of the B737 became aware of the conflict and stopped their position, potentially mitigating a collision. The result of these events was a runway incursion within the limits of a NMAC.

Case Number: 12
NTSB Accident Number: DCA12PA049
Date: 6 March, 2012

Summary: Perception and comprehension failures caused the controller to become diverged in the current divert weather, contributing to fuel exhaustion and terrain impact.

Synopsis: An approach controller's unknown divergence contributed to poor ATC services during an arrival sequence for a Kfir F-21, call sign Top Gun 29 (TG 29), at Naval Air State Fallon, Fallon, NV. After returning to the airport due to worsening weather, the first PAR approach for the aircraft was discontinued because of ATC personnel's inadequate preparation due to the poor weather forecast and the poor weather affecting the equipment. During the subsequent radar pattern vectors, the approach controller delayed turning the aircraft causing it to fly 53 nm in the pattern, worsening its fuel situation. The second PAR approach was terminated by the pilot and the pilot requested a divert to Reno Airport (RNO). However, RNO was below weather minimums, but that information was not passed to the pilot. Upon return to NAS Fallon, the pilot experienced fuel exhaustion and crashed short of the runway. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Response to Petition for Reconsideration, and Radar Data. Figure D-8 shows the ground track of the accident aircraft.

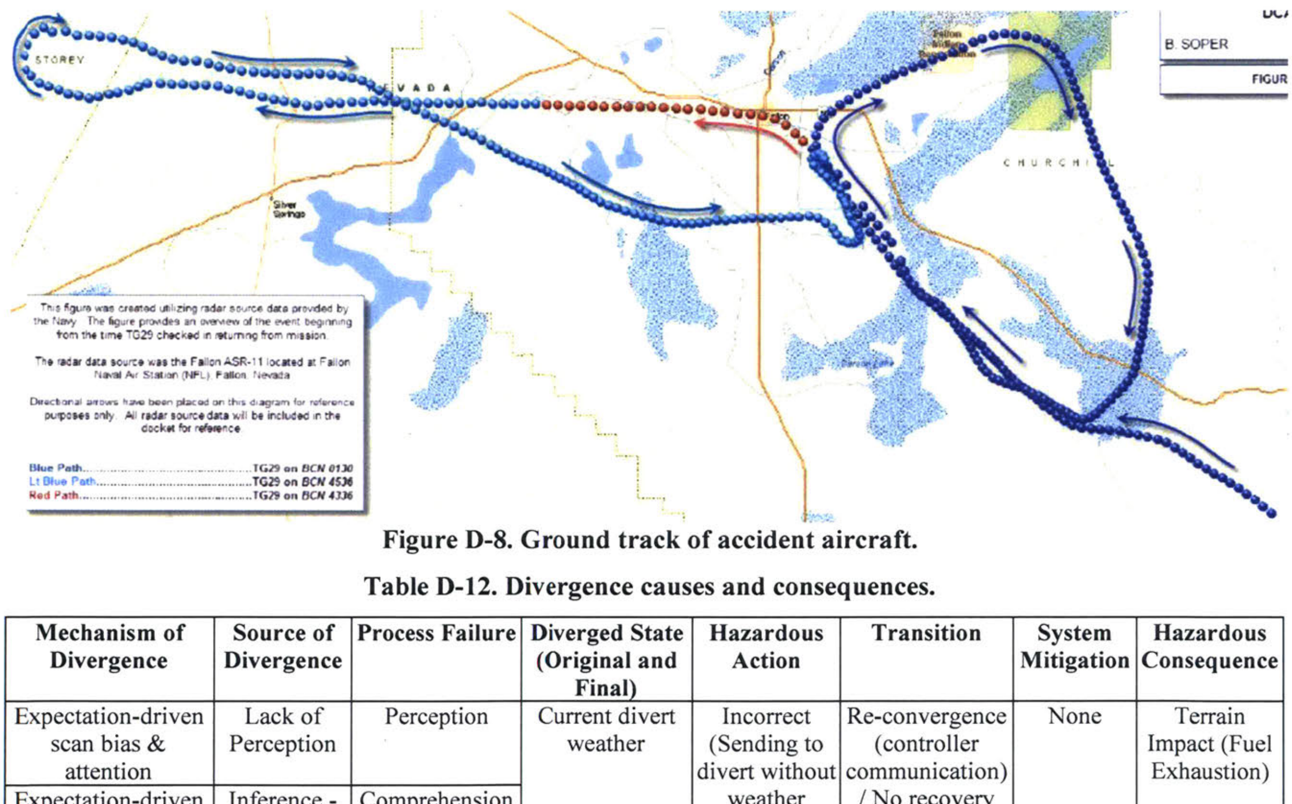

Figure D-8. Ground track of accident aircraft.

Table D-12. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Expectation-driven scan bias & attention	Lack of Perception	Perception	Current divert weather	Incorrect (Sending to divert without weather update)	Re-convergence (controller communication) / No recovery action (too late)	None	Terrain Impact (Fuel Exhaustion)
Expectation-driven comprehension bias	Inference - Guessing	Comprehension					

Divergence State: The controller experienced unknown divergence. Evidence of unknown divergence was based on NTSB investigation findings and the controller's testimony. The controller's state of divergence was likely the weather at RNO, which had become below approach minimums during the accident aircraft's flight. During the second PAR approach, the pilot requested to divert to RNO due to low fuel and poor weather at NAS Fallon. While the approach controller contacted Northern California

TRACON (NCT) to discuss the handoff, NCT stated they thought RNO was 'below minimums.' Although the approach controller replied 'roger,' he failed to relay this information to the accident pilot which caused unnecessary fuel burn during the flight.

Divergence Causes: Based on analysis, the cause of the unknown divergence was in part due to expectation-driven comprehension bias leading to an incorrect inference with no known observable for divert weather in the comprehension process. According to controller testimony, "He figured that since NCT had said earlier they seen clouds headed towards NFL, that by the time the accident pilot had requested to divert it was probably clear over at RNO." When NCT called back to say they couldn't take TG29, "he was surprised." The root cause of the expectation-driven comprehension bias was an incorrect projection of the weather based on an earlier observable. This expectation was combined with no updated observable due to expectation-driven scan bias regarding the weather at RNO, which the controller said when asked, "whether he looked at the weather for RNO once the accident pilot had requested to divert there, he said he had not." However, the controller did have an observable given to him during the handoff. When NCT accepted radar contact on TG29, NCT said they thought RNO was below minimums to the approach controller. In fact, the approach controller replied "roger" during the exchange, but failed to communicate this information to TG29 or comprehend how this would affect his status. This occurred due to an attention failure likely caused by high workload. During this time, the controller stated that "he remembered hearing someone ask what the weather at RNO was, but he said he had no time to answer because things were just crazy."

Divergence Consequences: After divergence, the controller committed an incorrect action by sending the aircraft to another frequency and continuing the divert process without warning the pilot of the weather. This led to a potentially hazardous situation of an emergency fuel status. The controller experienced re-convergence on the RNO weather before the accident occurred when NCT called the approach controller and reiterated that RNO was below minimums and the accident aircraft was returning to NAS Fallon. Although the controller re-converged, the aircraft was unable to land due to fuel exhaustion. Instead of ejecting, the pilot attempted an aggressive landing pattern, resulting in fuel exhaustion and terrain impact.

Case Number: 13
NTSB Accident Number: DCA12FA069
Date: 10 May, 2012

Summary: A working memory failure caused the controller to become diverged in the current medical requirements of an aircraft, which contributed to delayed medical assistance for a flight attendant.

Synopsis: An approach controller's unknown divergence contributed to delayed medical assistance for an injured flight attendant on a Frontier Airlines flight 384 landing at Fort Lauderdale Airport (FLL). The aircraft experienced turbulence on descent to the airport and the flight attendant was injured while securing the galley. As a result of the injury, the flight crew advised ATC that they had an injured crew member and requested priority handling and for paramedics to meet the airplane on arrival. However, the approach controller did not forward the request for paramedics, resulting in delayed medical response. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Final Report, NTSB Data Summary, and NTSB Docket, including the Pilot/Operator Aircraft Accident/Incident Report, Captain and First Officer Statements, Flight Data Recorder Specialist's Factual Report, Cockpit Voice Recorder Specialist's Factual Report.

Table D-13. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Working memory failure	Comprehension process	Current medical requirements	No action (not requesting paramedics)	None	None	Delayed medical assistance

Divergence State: The approach controller experienced unknown divergence. Evidence of unknown divergence was based on NTSB investigation findings and pilot testimony. According to the NTSB, "At 1229, the Captain asked Miami Approach Control to make sure there were no delays into FLL and to call for paramedics to meet the flight at the gate. The controller acknowledged, and advised there would be no delay." However, this approach controller briefed another controller to take over at 1233, but "there was no mention of the request for paramedics." According to the pilot incident report, "due to training being conducted, approach control failed to relay this information [request for medical assistance] to KFLL tower." When the aircraft arrived at the gate, there was no awareness of the request for medical assistance, significantly delaying this action. It appears the state of divergence during this incident was the aircraft's current medical requirements. According to the NTSB Final Report, the ATC personnel had a "forgotten action/omission."

Divergence Causes: The cause of the divergence was determined to be a working memory failure in the comprehension process. However, it is not apparent what caused the working memory failure in this case.

Divergence Consequences: The diverged controller failed to request medical assistance or pass along the request to another controller (hazardous action – no action). This led to a potentially hazardous situation or no medical assistance dispatched. Although medical assistance was eventually received, there was no evidence of a transition to known divergence or re-convergence for the approach controller. In addition, the crew attempted to coordinate medical assistance with the airline on arrival, but could not establish communications due to improper staffing. These events led to the delayed medical assistance for the flight attendant.

Case Number: 14
NTSB Accident Number: ERA12FA409
Date: 22 June, 2012

Summary: A projection failure caused the controller to become diverged in the future position of an aircraft, which contributed to a CFIT with an obstacle.

Synopsis: An approach controller's unknown divergence contributed to a Raytheon-Beech King Air C90 striking a commercial broadcast antenna located approximately 8 miles northeast of the Morgantown Municipal Airport (MGW), Morgantown, WV, killing the single pilot. The flight was operating during day VFR, taking off from Nemacolin Airport (PA88), Farmington, PA on a repositioning flight of 19 nm to MGW under CFR Part 91. At the time of the accident, the pilot was receiving flight following radar services from approach control located near Clarksburg, WV, with no flight plan filed. During the accident, the pilot received no safety alert regarding the proximity of the tower. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, Witness Statements and Interview Summaries, Maps and Charts of Accident Area – Radar Data Overlays, Maps and Charts of Accident Area – Radar Display Map with Radar Data Overlay, Chronological Summary of Flight and Transcriptions of Recorded Conversations, and Cockpit Voice Recorder – Factual Report of Group Chairman. Figure D-9 shows the ground track of the accident aircraft.

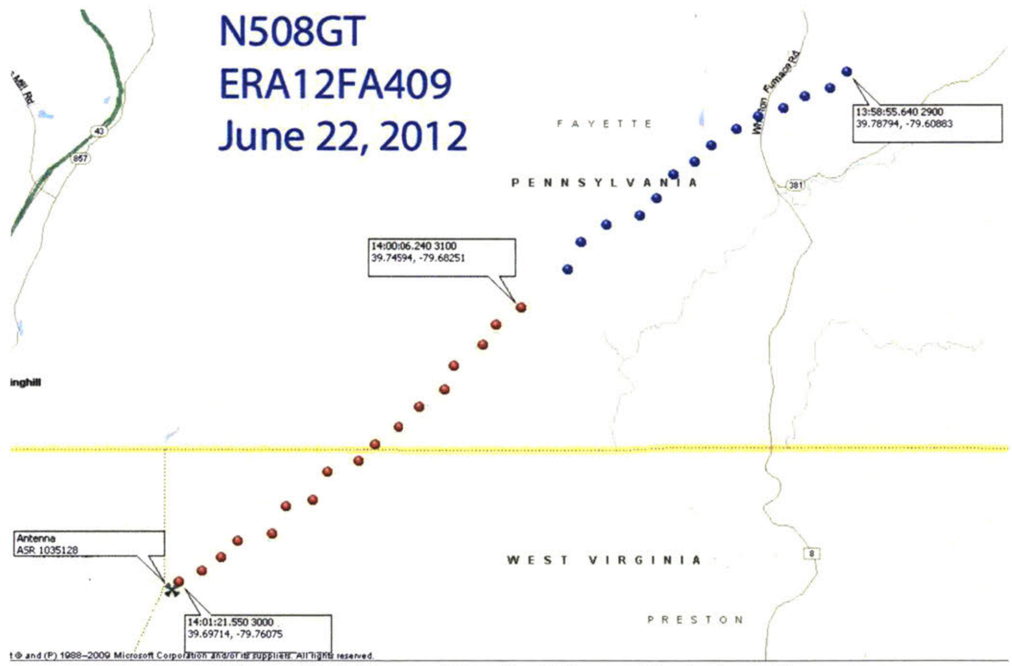

Figure D-9. Ground track of the accident aircraft.

Table D-14. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Mental simulation	Projection process	Future aircraft position → Future aircraft separation	No action (not providing a safety alert)	None	None	CFIT

Divergence State: The approach controller experienced unknown divergence. Evidence of unknown divergence is based on the accident occurring without controller awareness and controller testimony of inconsistent state awareness versus the actual system. The NTSB ATC Group Chairman's Factual Report stated "Mr. Pisanti radar identified the aircraft approximately 9 miles east of Morgantown at 3100 feet, instructed the pilot to maintain VFR, and asked if he had the weather information for the airport. The pilot replied that he was 'getting it.' Mr. Pisanti stated that he then worked some other aircraft, came back to the accident aircraft, and noticed that it was gone." In addition, when asked why he did not provide a safety alert, "Mr. Pisanti stated that he did not believe that the antenna, '...would be a factor'." The controller's state of divergence appears to be the future separation between the aircraft and the tower, propagated from a divergence of the future position of the aircraft. According to the NTSB ATC Group Chairman's Factual Report, "His impression when he radar identified the accident aircraft was that it would be passing north of the antenna."

Divergence Causes: It appears the future aircraft position state diverged due to a mental simulation error within the projection process, causing an incorrect projection of future separation between the aircraft and the tower. The controller appeared to perceive and comprehend the required information to project the future position of the aircraft in relation to the tower. In addition, there was no evidence of another input error to the projection process itself.

Divergence Consequences: The diverged controller provided no safety alert (hazardous action – no action) which failed to mitigate the potentially hazardous situation (aircraft-to-obstacle conflict) that had already developed. The pilot's inadequate route choice along with flying under VFR led to the conflicting trajectory. The NTSB cited the pilot's inadequate pre-flight route planning and in-flight route and altitude selection as the probable causes of the accident, which led to the inadequate route choice as shown in Figure D-9. However, the pilot did contact approach control enroute to the Class D airport, which was not required. There was no evidence of known divergence or re-convergence before the accident. However, this failed projection could have been mitigated by an updated perception of the aircraft, leading to an updated projection of its position relative to the tower prior to the accident. In testimony, after the pilot state that he was getting the weather information, "Mr. Pisanti stated that he then worked some other aircraft, came back to the accident aircraft, and noticed it was gone." According to the NTSB investigation, at least 51 seconds elapsed between the pilot's final radio call that he was getting the weather and the last radar return prior to obstacle impact. During this time, it appears the controller did not perceive any information regarding the accident aircraft, which could have led to an updated projection and decision to pass a safety alert. Due to the comments that the tower "would not be a factor" and the lack of a visual scan towards the accident aircraft, the controller likely failed to perceive the aircraft during the 51 seconds due to an expectation-driven bias and attention allocation issue, ultimately leading to a failure of the controller to transition to re-convergence before the accident. Also, the pilot had inhibited the Ground Proximity Warning System (GPWS) 20 seconds before landing at PA88, the departure airport for this flight, which according to NTSB findings would have alerted the pilot to the tower before impact. Finally, poor VLO failed to mitigate this accident, leading to a CFIT.

Case Number: 15
NTSB Accident Number: OPS12IA849
Date: 31 July, 2012

Summary: A perception failure caused a controller to become diverged in the current approach runway in use, contributing to a LoSS. A comprehension failure caused the same controller to become diverged in the aircraft identity of his supervisor's command, contributing to another LoSS.

Synopsis: A tower controller's unknown divergence contributed to a LoSS between an arriving aircraft, EMB170 (RPA3329), and a departing aircraft, EMB135 (CHQ3071) at Washington-Reagan National Airport (DCA). Their unknown divergence contributed to another LoSS between the same arriving aircraft and another departure aircraft, EMB170 (RPA3467). All flights were operating on IFR flight plans and CFR part 121 during day VMC. Due to miscommunications between approach control and tower over a land line, the tower facility continued operations on runway 01 while the approach facility began operations on runway 19, opposite direction. While the controller departed two aircraft on runway 01, approach control cleared RPA3329 for a visual approach runway 19, causing two instances of LoSS. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the Air Traffic Mandatory Occurrence Report and Radar Graphic with Weather Overlay. Figure D-10 shows RPA3329 and CHQ3071 flight paths and separation while Figure D-11 shows RPA3329 and RPA3467 flight paths and separation.

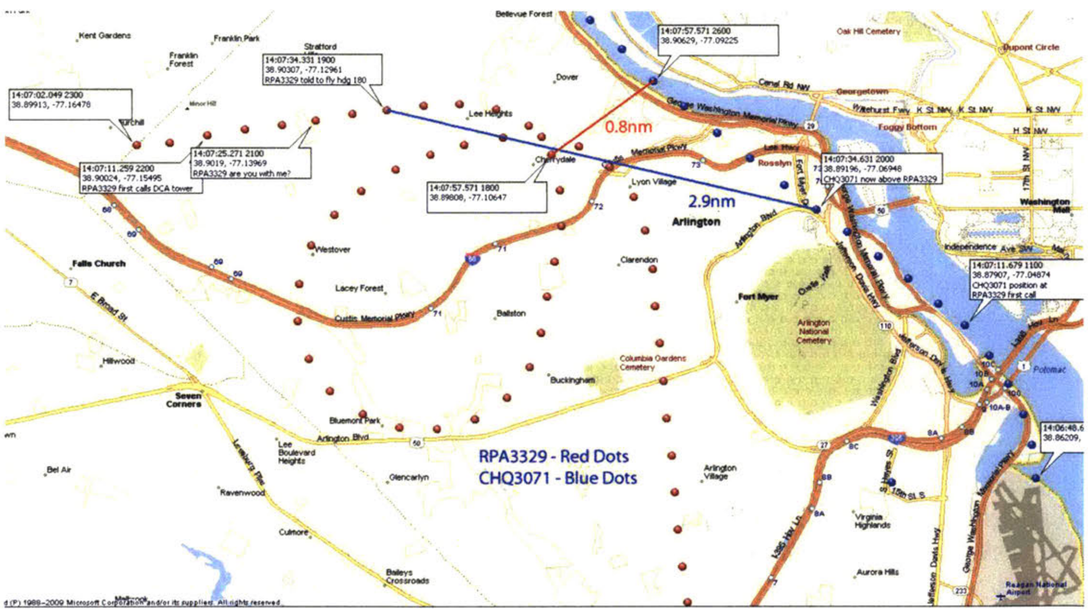

Figure D-10. RPA3329 and CHQ3071 flight paths and separation.

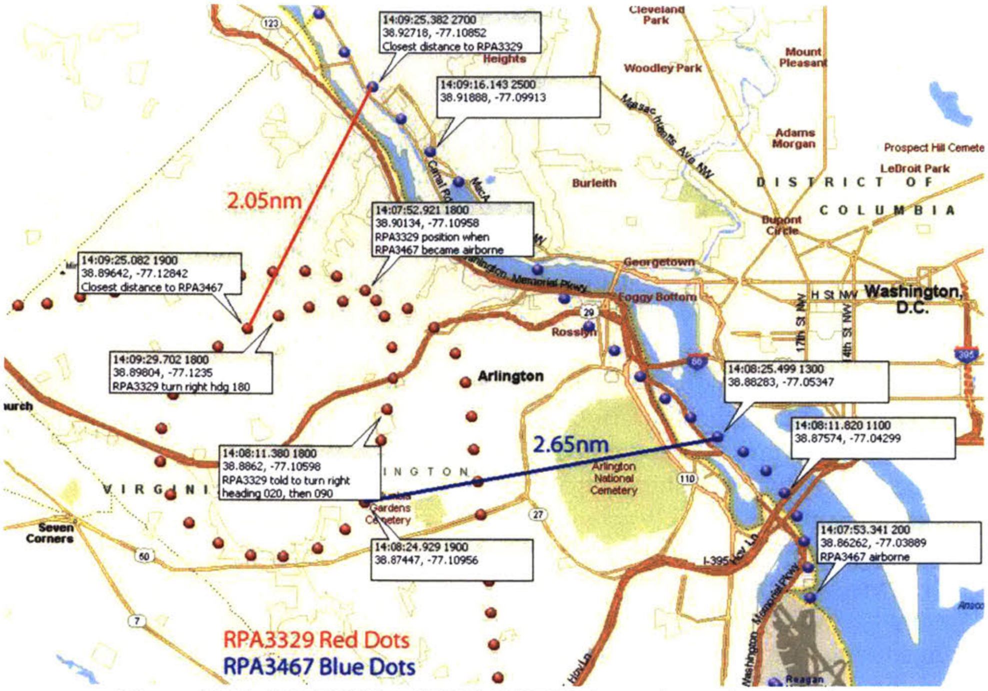

Figure D-11. RPA3329 and RPA3467 flight paths and separation.

Table D-15. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Human error	Inaccurate observable	Perception	Current approach runway → Future aircraft separation	Incorrect (takeoff clearance)	Known divergence (aircraft communication)	None	LoSS
Expectation-driven comprehension bias	Inference - Guessing	Comprehension	Aircraft identity → Future aircraft separation	Incorrect (vector)	Re-convergence (TSD) / Recovery action (vectors)	None	LoSS

Divergence States: Misunderstanding between the tower's Traffic Management Coordinator (TMC) and TRACON's TMC propagated to the Local Controller (LC) who experienced unknown divergence. Evidence of unknown divergence is based on controller testimony and a LoSS with both aircraft following ATC instructions. During post-accident interviews, the LC stated to the NTSB the "TMC1 [Traffic Management Coordinator 1] came to the position and advised her and the ALC [Assistant Local Controller] controller that PCT [Potomac TRACON] needed to reduce spacing on the final approach to get in more arrivals." Due to this misunderstanding, the LC continued with departures from runway 01 and allowed both CHQ3071 and RPA3467 to depart runway 01. It appears the first diverged state was the current approach runway state.

The LC experienced unknown divergence again based on controller testimony and a LoSS with both aircraft following ATC instructions. During post-incident interviews, the LC stated to the NTSB that during the events, the supervisor told her to "turn him right" to a heading of 020 and then heading 090. Although the supervisor meant RPA3467, the departing aircraft, the controller had just been speaking with RPA3329, the aircraft previously cleared for the visual approach. Therefore, the continued right hand turns of RPA3329 with the continued departure of RPA3467 caused a LoSS. It appears the diverged state was the current aircraft identity state, diverged between the LC and the supervisor.

Divergence Causes: The LC's appears to have first diverged based on the inaccurate observable received form the TMC. This divergence propagated to a diverged future separation state between CHQ3071 and RPA3329.

The LC appears to have diverged a second time because of the combination of expectation-driven comprehension bias and an ambiguous observation, leading to an incorrect inference. As stated earlier, the supervisor told the LC to "turn him right" while the controller was working both RPA3329 and RPA3467. The controller assumed the supervisor meant RPA3329, most likely because that is who she had just communicated with and was the cause of the LoSS prior. However, this expectation was incorrect and the supervisor had meant her to vector the departure aircraft RPA3467.

Divergence Consequences: Once diverged, the LC cleared the CHQ3071 for takeoff (hazardous action – incorrect action) leading to an aircraft-to-aircraft conflict (potentially hazardous situation). However, there was evidence of a transition to known divergence, based on the observable of RPA3329 on right base and communicating with tower and controller testimony. Upon receiving the observable from the pilot, a communication stating RPA3329 inbound "on the river," the LC looked for aircraft on the south side of the airport using the tower radar display. She then verified the call sign and the pilot again responded "on the river." Upon cross-checking the tower radar display again, she saw RPA3329 approximately 5 nm northwest of the airport. According to testimony, the controller stated "the aircraft was coming from an unusual place that didn't immediately cause her to realize that the aircraft was on a visual approach to runway 19." Regardless, this led her to giving a vector to RPA3329 to turn to heading 180 in order to clear the departure corridor. At this point, the aircraft had passed their closest point of approach. Although there was no evidence of re-convergence before the incident, the known divergence led the controller to command a vector and give a traffic alert to RPA3329 still potentially unaware of the cause of RPA3329's position. Combined with VLO from both aircraft, the result of the incident was a LoSS.

Once diverged the second time, the LC vectored the wrong aircraft, RPA3329 (hazardous action – incorrect action) leading to an aircraft-to-aircraft conflict (potentially hazardous situation). However, there was evidence of a transition to known divergence and re-convergence during this event. Evidence of the transition to known divergence and re-convergence was based on the strategy change of the LC and testimony. Following the heading of 090, the controller continued providing vectors to a heading of 180 to continue to provide RPA3329 clear airspace outside of the departure corridor. The controller continued to vector the aircraft, resulting in a LoSS.

Case Number: 16
NTSB Accident Number: ERA13LA042
Date: 28 October, 2012

Summary: A projection failure caused a controller to become diverged in an aircraft's future terrain separation, contributing to a CFIT.

Synopsis: A departure controller's unknown divergence contributed to a Piper PA-32R-300, N4478F, CFIT after departing Gatlinburg-Pigeon Forge Airport (GKT), Sevierville, TN. The flight departed in IMC under IFR. After departure, the controller asked the pilot if he would like radar vectors rather than the filed departure procedure, which the pilot responded affirmative. After approximately 2 minutes under radar vectors, the pilot received and communicated a terrain warning on his GPS, but received no response prior to terrain impact. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Aviation Accident Final Report, and NTSB Docket, including the ATC Group Chairman's Factual Report, Accident Communication Transcripts, Pilot Telephone Interview Transcript, and Pilot and Passenger Statements. Figure D-12 shows the ground track of the accident aircraft.

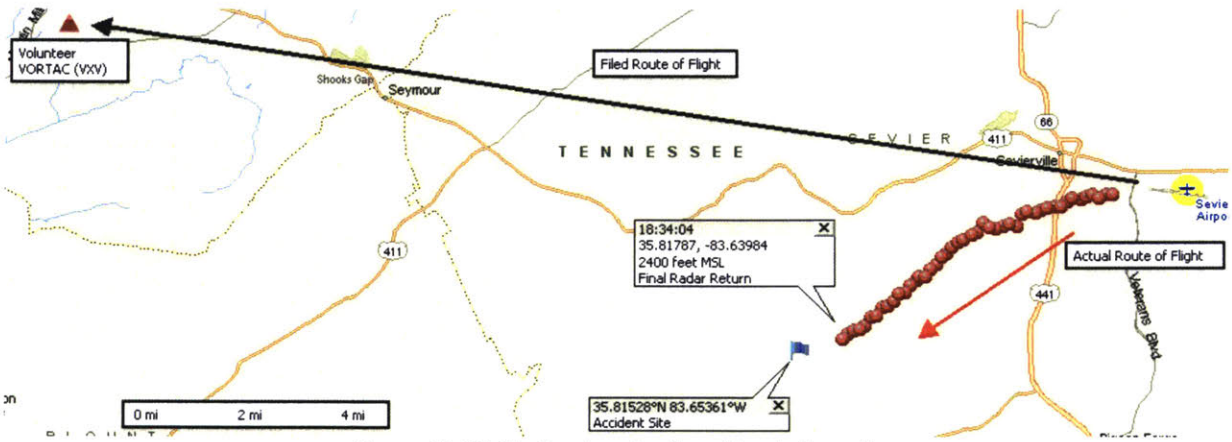

Figure D-12. Radar track of accident aircraft.

Table D-16. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Mental Simulation	Projection	Future terrain separation	Incorrect (vector)	Known divergence (pilot communication)	TAWS	CFIT

Divergence State: The controller experienced unknown divergence. Evidence of unknown divergence is based on controller testimony and communication transcripts. During post-accident interviews, the radar controller stated to the NTSB the he "had issued N4478F a heading and altitude and considered the situation well in hand," signifying no awareness of the possibly conflicting trajectory of the aircraft with terrain ahead. In addition, after the issuance of the heading and altitude by the controller at 1832:02, there were no other communications until 1834:04 when the pilot of the accident aircraft stated, "Knoxville seven eight fox uh we're getting a terrain advisory we still in the clear?" It appears the diverged state was the future terrain separation state. The controller did not fully understand the future terrain separation of the aircraft following the controller's initial vector of the aircraft after departure.

Divergence Causes: The cause of the divergence was likely a mental simulation failure in the projection process, which led to an inaccurate projection of the future terrain separation along the aircraft's route of flight into the near future. During the early stages of the aircraft's departure, the controller asked the pilot if he would like vectors rather than fly the planned departure routing, which the pilot agreed to. The initial vector given by the controller, combined with a minor heading deviation of the pilot, let to the conflicting trajectory form the beginning. The controller stated in testimony that "the pilot was climbing slowly and tracking about 240 to 250 degrees."

Divergence Consequences: Once diverged, the departure controller commanded a vector (hazardous action – incorrect action) which led to an aircraft-to-terrain conflict (potentially hazardous state). The vector was a violation of standard operating procedures based on the aircraft's altitude below the MVA. After the initial conflicting trajectory, the controller failed to update this projection due to a lack of perception based on the controller focusing his attention on working the FPS and not the TSD. Later, the controller appeared to transition to known divergence before terrain impact. Evidence of the transition to known divergence was based on the communication transcripts. Upon receiving the observable from the pilot regarding the terrain advisory, the controller had four transmissions of unintelligible or incoherent communication, signifying known divergence as he brought up the minimum enroute IFR altitude map. Yet the controller failed to provide an adequate vector or safety alert for the pilot due to the pilot's working memory failure of obstacles in the area combined with a lack of perception of obstacles due to his personal setting of not having that information on the TSD. According to the NTSB by the time the controller observed the map and developed a response to the pilot, the pilot did not respond. Therefore, there was no evidence of re-convergence before the accident.

Case Number: 17
NTSB Accident Number: ERA13FA088
Date: 16 December 2012

Summary: A comprehension failure caused a controller to become diverged in the aircraft's gyroscopic system capability, contributing to a loss of control and terrain impact.

Synopsis: An approach controller's unknown divergence contributed to a Piper PA-28, N5714W, loss of aircraft control and subsequent terrain impact near Parkton, NC. The pilot departed Summerville Airport (DYB), Summerville, SC, and was destined for Fayetteville Regional Airport (FAY), Fayetteville, NC. The flight was being vectored for an ILS approach to runway 4, handed off to the tower controller, but failed to fly a successful approach, flying S-turns and stating to the tower controller that he was "having a little bit of trouble now and I seem to have lost some gyros." After the unsuccessful approach, the tower controller handed the aircraft back to approach control. Then, the pilot requested a climb and routing to his alternate airfield. However, after continued heading and altitude deviations, the controller asked if he could accept no-gyro vectors for another attempt at the ILS at FAY. During this approach, the pilot lost control of the aircraft and crashed. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Aviation Accident Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Controller's Personnel Statements, Witness Statements, and communication transcripts. Figure D-13 shows the ground track of the accident aircraft.

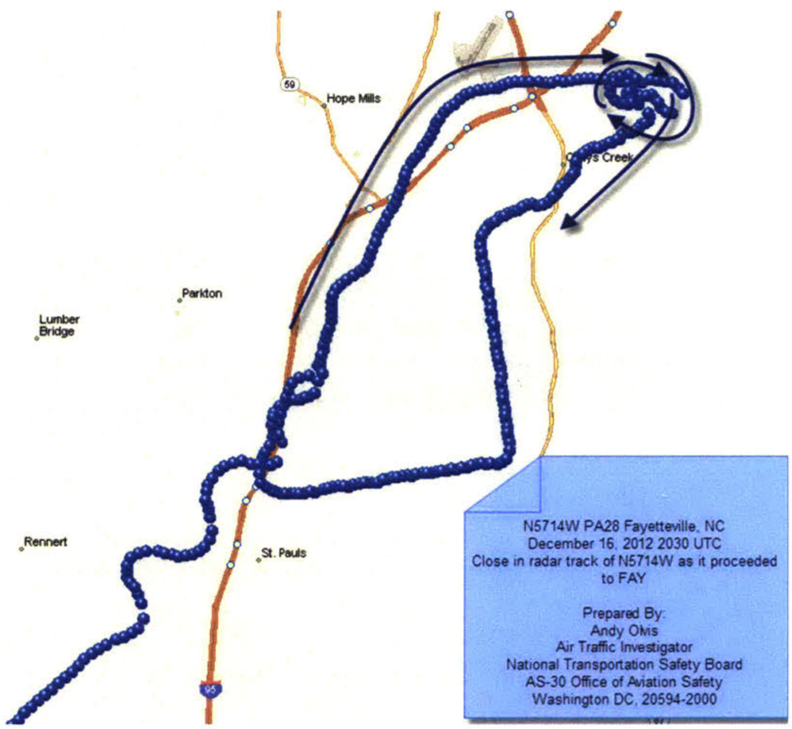

Figure D-13. Ground track of the accident aircraft.

Table D-17. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Incorrect knowledge	Association	Comprehension	Gyroscopic system	Incorrect (no-gyro vectors)	Known divergence (TSD)	None	Terrain Impact (Loss of control)
Unknown	Integration						

Divergence States: The controller experienced unknown divergence. Evidence of unknown divergence is based on controller testimony and non-conservative controller strategies for the situation. During post-accident interviews, the local controller, approach controller, and supervisors all stated that their understanding of a loss of gyros meant the pilot may have trouble maintaining heading, but were unaware that this emergency may affect the pilot's attitude information and that continued flight in IMC would potentially add risk. In addition, the controller's decision to attempt another ILS approach using no-gyro vectors rather than a climb to VMC and divert to a VFR alternate airfield signify unknown divergence. It appears the state of divergence was the current aircraft gyroscopic state. The controller did not fully understand the implications of the loss of gyro instruments in the aircraft.

Divergence Causes: The NTSB cited a contribution to the accident as "the inadequate recurrent training of FAA ATC personnel in recognizing and responding to in-flight emergency situations." The cause of the divergence in the current gyroscopic system state was likely based on incorrect knowledge of the emergency situation and its ramifications, or an association failure in the comprehension process. However, this communication regarding the 'no-gyro' state was not the only observables available to the controller. The altitude and heading deviations, in addition to the communication from the pilot that "I'm not okay right now" should have led to an understanding of the state of the system. Therefore, there was a likely integration failure in the comprehension process leading to the divergence. Later, the controller asked if the pilot wanted to land back at the airport [FAY]. The pilot responded with "uh the best thing to," but the communication was incomplete and therefore ambiguous. Although this observable was determined by the NTSB to likely have been the pilot intending to tell the controller again that he wanted to go to his alternate airport, which was VMC, the controller likely incorrectly inferred this to mean an affirmative reply based on expectation bias from the incorrect knowledge of the system state. Here, the NTSB cited a contribution to the accident as "the inadequate assistance provided by FAA ATC personnel."

Divergence Consequences: Once diverged, the controller provided no-gyro vectors (hazardous action – incorrect action) leading to a loss of control (potentially hazardous state). The controller appeared to transition to known divergence toward the end of the flight. Evidence of the transition to known divergence was based on controller testimony, where the controller "believed the flight had been an emergency in the last stages of the flight, just before the final radar targets." However, the controller still did not understand the specific nature of the consequences of the emergency situation with no gyros. Therefore, there was no evidence of re-convergence before the accident.

Case Number: 18
NTSB Accident Number: ERA13FA105
Date: 4 January, 2013

Summary: A projection failure caused a controller to become diverged in an aircraft's future engine operability, contributing to terrain impact.

Synopsis: An approach controller's unknown divergence contributed to a Beechcraft H35, N375B, landing approximately 1 nm short of the runway after experiencing a total loss of engine power. The pilot and two passengers departed Saint Lucie County International Airport (FPR), Fort Pierce, FL, and were destined for Knoxville Downtown Island Airport (DKX), Knoxville, TN. The pilot reported a "vibration in the prop" and "an oil pressure problem" to the controller while enroute at 7,500 feet MSL. IMC prevailed along the Florida coast at the time of the accident, with cloud ceilings between 900 and 1,000 feet AGL. The pilot received radar vectors for an Airport Surveillance Approach (ASR) to runway 29 at Flagler County Airport (XFL), Palm Coast, FL. During the vectors, the pilot reported "zero oil pressure, but we've got cool cylinder head temperature." However, during the approach the aircraft was vectored 6.5 nm around the far side of the airport before being vectored to base and final. On final, the aircraft apparently lost total engine power and crashed short of the runway. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Aviation Accident Data Summary, and NTSB Docket, including the ATC Group Chairman's Factual Report, Controller's Personnel Statements and Witness Statements. Figure D-14 shows the ground track of the accident aircraft.

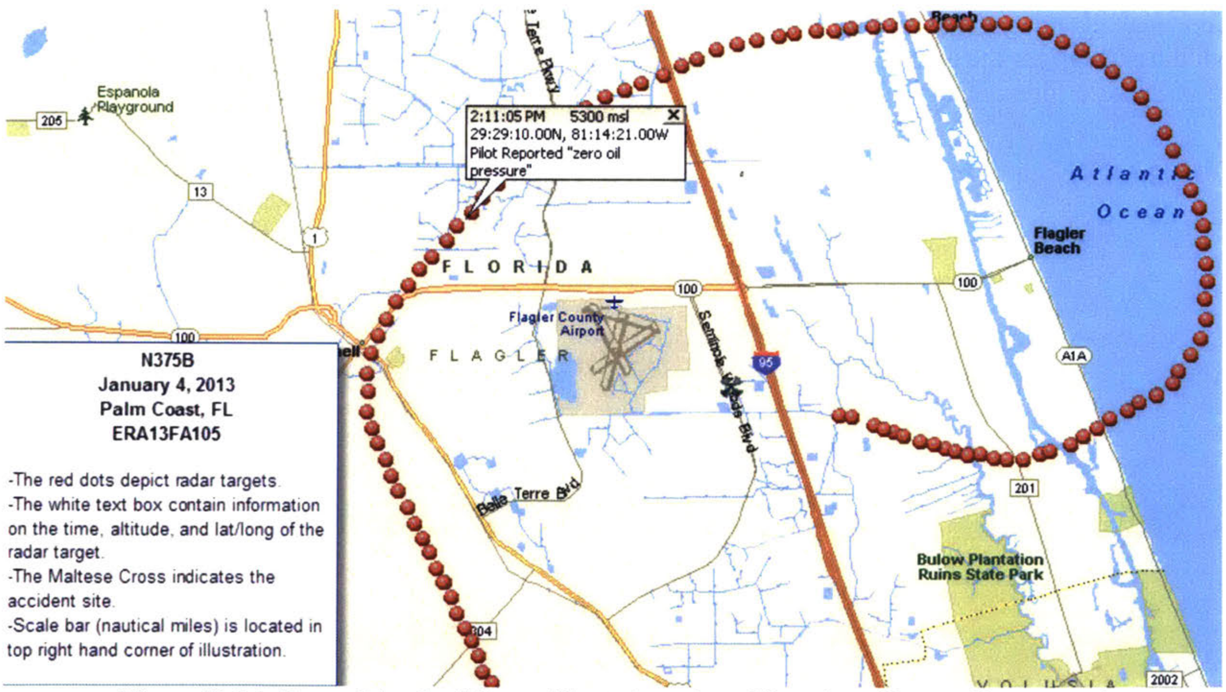

Figure D-14. Ground track of the accident aircraft and location of 'zero oil pressure.'

Table D-18. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Incorrect knowledge	Projection	Future engine operation	Incorrect (vectors)	None	None	Terrain Impact

Divergence state: The approach controller experienced unknown divergence. Evidence of unknown divergence is based on the total engine power loss and subsequent accident following properly executed controller commands. After the pilot stated the aircraft had "zero oil pressure," the controller said he did feel "an increased sense of urgency," but did not want to descend the airplane too fast or slow, nor turn him too quickly. The controller wanted to keep the airplane in close to the airport, but not too close on the downwind because of obstacles. According to the NTSB, a contributing factor to the accident was the "air traffic controllers' incomplete understanding of the emergency, which resulted in the controllers vectoring the airplane too far from the airport to reach the runway." Based on analysis, it appears the state of divergence was the future aircraft engine state. The controller received awareness of the engine anomaly from the pilot's communication of a "vibration in the prop" and "we've got an oil pressure problem; we're going to have to drop quickly here." However, the NTSB cited "incomplete understanding of the emergency" in the NTSB Synopsis as contributing to the accident.

Divergence causes: The cause of the divergence was likely based initially on incorrect knowledge into the mental model used in the projection process, which projected an incorrect future aircraft engine state. Based on this incorrect input, the controller potentially assumed the aircraft would have sufficient power for the vectors the controller planned to give the pilot.

Divergence consequences: Once diverged, the controller provided incorrect vectors (hazardous action – incorrect action) that failed to mitigate the engine emergency (potentially hazardous situation). There was no evidence of known divergence or re-convergence before the accident. This divergence never transitioned to known divergence or re-convergence despite an ambiguous communication from the pilot of "zero oil pressure, but we've got cool cylinder head temperature." After this transmission, the pilot never updated the controller with additional observables, which led to the controllers continued divergence and poor plan. Overall, these conditions led to the controller providing vectors too far away from the runway for the engine power available. When the aircraft lost complete engine power, the aircraft made a forced landing approximately 1 nm short of the runway.

Case Number: 19
NTSB Accident Number: ANC13FA030
Date: 8 March, 2013

Summary: A comprehension failure caused a controller to become diverged in pilot intent, contributing to a CFIT.

Synopsis: An approach controller's unknown divergence contributed to a twin-engine turboprop Beech 1900C striking rising terrain about 10 miles east of Aleknagik, Alaska, killing two pilots. The flight was operating during day IMC under IFR between King Salmon and Dillingham, Alaska under CFR Part 135. At the time of the accident, the pilot was receiving radar services from the Anchorage ARTCC (ZAN). Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, Operational Factors / Human Performance Group Chairman's Factual Report, Anchorage Center "Lessons Learned" Briefing, and various maps and charts. Figure D-15 shows the ground track of the accident aircraft.

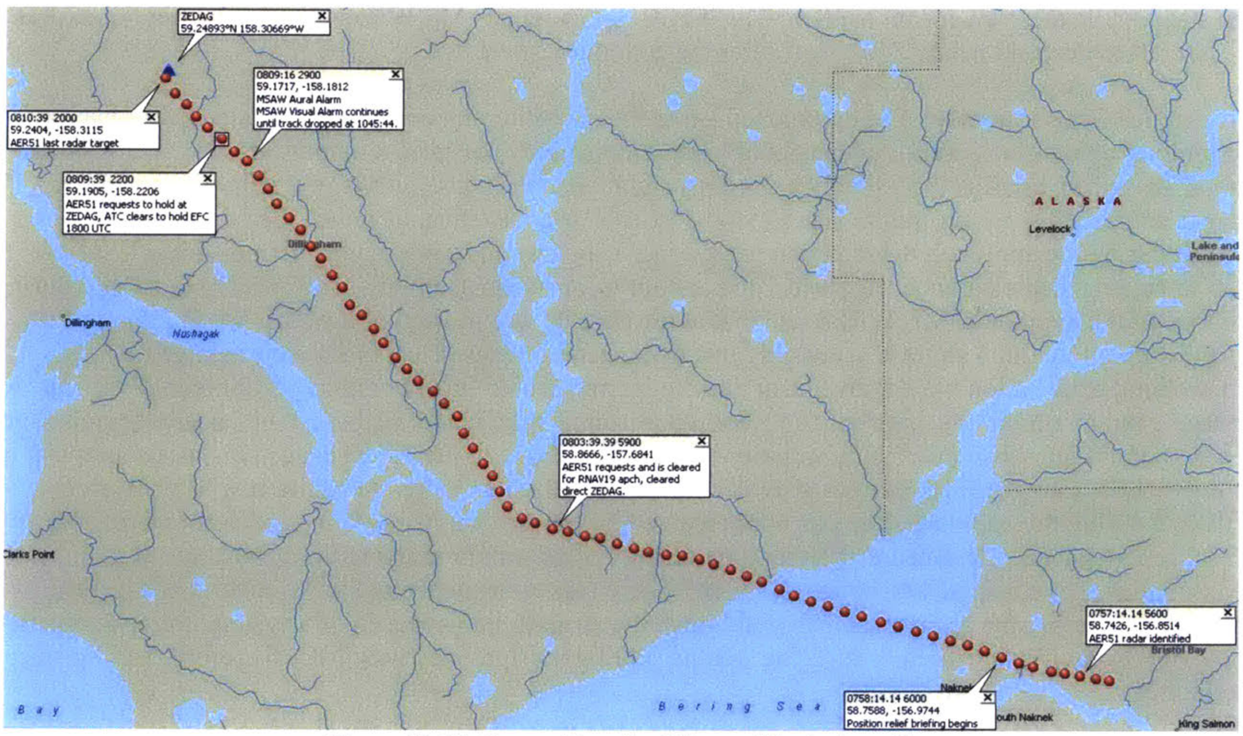

Figure D-15. Ground track of the accident aircraft.

Table D-19. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Expectation-driven comprehension bias	Association	Comprehension	Pilot intent → Future terrain separation	No action (no read-back correction)	None	None	CFIT

Divergence State: The approach controller experienced unknown divergence based on evidence of an accident without the controller's awareness, unknown flight below minimum altitude clearance, unacknowledged safety alerts, controller and pilot miscommunication, and controller testimony of incongruent state awareness versus the actual system. When asked about the safety alerts, the NTSB ATC

Group Chairman's Factual Report stated "Mr. Wicks stated that he was not consciously aware that the MSAW alert was going off, and therefore did not have any immediate concern that the aircraft was producing an alert." There was evidence the controller and pilot miscommunicated during the initial approach clearance, specifically the altitude cleared. For instance, the NTSB report stated "AER51 cleared … maintain well maintain at or above two thousand until established on a published segment of the approach," while the pilot read back "cleared to … maintain two thousand until a published segment of the approach AER51." The controller did not correct this transmission. According to testimony, "Mr. Wicks said that he did not expect the aircraft to descend below 5400 feet, and did not notice when the pilot did so." Based on analysis, it appears the state of divergence was the current pilot intent, leading to a divergence in the future state projection of the position state and future terrain separation.

Divergence Causes: First, the crew misunderstood the approach clearance given by the controller, which may have been caused by an ambiguous clearance given. According to the Operations Manager, after reviewing a reply of the accident, "He heard the approach clearance given and described it as, 'not good'." However, this misunderstood clearance was read back to the controller. The current pilot intent state likely diverged due to an expectation bias of the pilot's read back to comprehend the read-back as one state, while the crew meant another. The NTSB report stated "Mr. Wicks said that he did not expect the aircraft to descend below 5400 feet" after the communication.

Divergence Consequences: The divergence led to the controller not correcting the pilot's read back (hazardous action – no action), which could have re-converged the current intent states. This created an aircraft-to-terrain conflict (potentially hazardous situation). The consequence of the divergence could have been mitigated by several means. First, the controller could have perceived the position of the aircraft during the approach, which upon perceiving, may have led to the controller providing a safety alert or an amended clearance. However, due to poor information sampling (The NTSB report said during the time of the approach "Mr. Wicks said that at the time he was in front of the strip board looking for information on inbound aircraft") possibly due to expectation bias (The NTSB report stated that "His [controllers] expectation would have been that the aircraft would stay at or above 5400 feet all the way to Zedag.") and an observable barrier (The NSB report stated "Mr. Wicks stated that he usually spends time nearer to the flight strips and the information display to the side of the radar scope. This was somewhat of an ergonomic issue."), the controller provided no additional safety alerts. In addition, a MSAW alert activated during the approach, but was not perceived due to the observable being indiscriminate. The NTSB report stated, "He noted that either a recurring aural alarm or relaying the aural alarm into his headset might have helped him notice the alert." There was no evidence of known divergence or re-convergence before the accident. Finally, although the aircraft did have a GPWS system, the investigation could not reveal if it activated or not. The weather during the approach was IMC; therefore, VLO proved ineffective.

Case Number: 20
NTSB Accident Number: DCA14IA037
Date: 12 January 2014

Summary: A perception and comprehension failure caused an approach controller to become diverged in the pilot intent, contributing to a wrong airport landing.

Synopsis: An approach controller's unknown divergence contributed to a Southwest Airlines B-737 landing at M. Graham Clark Downtown Airport (PLK), 6 miles north of the intended destination, Branson Airport (BBG), Branson, Missouri. The flight was operating during night VMC under IFR between Chicago and Branson under CFR Part 121. At the time of the incident, the pilot was receiving radar services from the terminal radar approach control facility located at the Springfield-Branson National Airport (SGF), Springfield, Missouri. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, Operational Factors Interview Summaries, Personnel Statements, Communication transcripts, and FAA Memorandum on Mandatory Briefing for Wrong Airport Arrival. Figure D-16 shows the ground track of the incident aircraft.

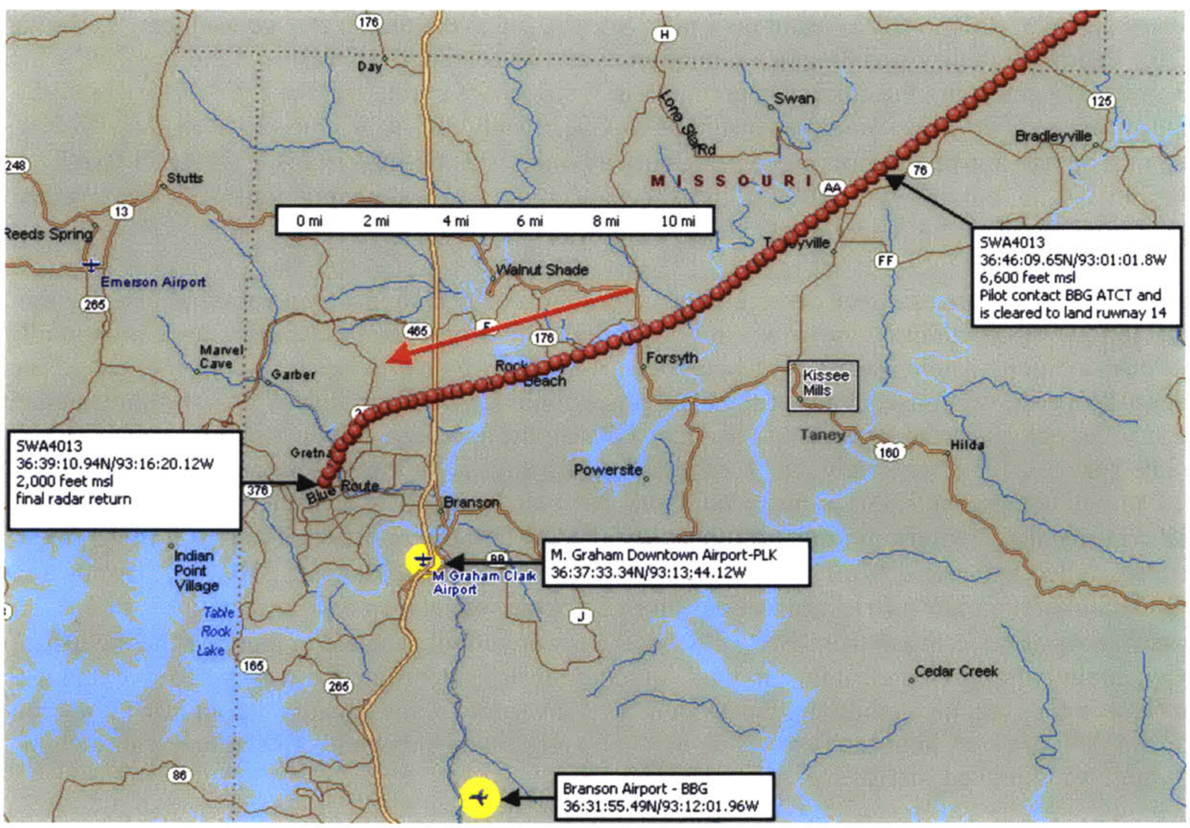

Figure D-16. Ground track of incident aircraft.

Table D-20. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Human error	Inaccurate observable	Perception	Pilot intent → Future aircraft position	Incorrect (cleared aircraft to tower)	None	None	Wrong Airport Landing
Expectation-driven comprehension bias	Inference - Guessing	Comprehension					

Divergence state: The approach controller provided an inaccurate point out to the aircraft regarding the airport position. According to the NTSB report, "At 1802:50, the SGF approach controller advised the pilot of SWA4013 that the airport was at his 11 o'clock position and 15 miles. Radar data indicated that that the airport at SWA4013's 11 o'clock at 15 miles was PLK, not the destination airport, BBG. BBG was approximately 20 miles from SWA4013." The pilot then reported the field in sight; however, the airport was PLK rather than the intended BBG. This resulted in an unknown divergence between the crew and controller based on the evidence of an incident without the controller's awareness and controller and pilot miscommunication. First, the NTSB report stated "After SWA4013 advised BBG that they had landed at the wrong airport at 1809:45; the BBG controller confirmed that SWA4013 had landed and called SGF to ask if the approach controller had observed SWA4013 land at PLK. The approach controller advised that SWA4013 had dropped off radar near PLK," illustrating no knowledge of the wrong airport landing. It appears the diverged state was the current pilot intent, leading to a divergence in the future state projection of the position state.

Divergence causes: First, the pilot identified the incorrect airport as the intended destination after the inaccurate pointout, which became an inaccurate observable to the controller. Combined with a lack of a nearby airport pointout (NTSB report stated, "The approach controller did not advise SWA4013 of the close proximity of PLK to BBG.") and poor pilot SA, this led to the pilot's change of intent. At the same time, the controller understood the pilot's ambiguous and inaccurate read back of "field in sight" (NTSN full narrative) as meaning the correct airport, possibly influenced by the fact the SWA4013 was GPS equipped (expectation-driven comprehension bias). Specifically, the NTSB report stated "Mr. Hobbs stated that he had applied airport close proximity advisories as defined in FAA Order 7110.65, paragraph 7-4-3g, but not with GPS equipped aircraft unless they appeared confused." This led to an incorrect inference of the meaning of "field in sight."

Divergence consequences: Once diverged, the controller provided an incorrect action of clearing the aircraft to tower (hazardous action), contributing to the pilot's non-clearance conformance (potentially hazardous situation). There was no evidence of controller known divergence or re-convergence before the incident. However, the consequence of the divergence could have been mitigated by several means. First, the controller perceived the position of the aircraft during the approach, but did not comprehend or project this trajectory to be in error, likely due to expectation-driven bias for the reasons described before. If the controller had comprehended or projected an issue, he could have provided a safety alert to the crew. The NTSB report stated, "After communications with SWA4013 were transferred to BBG, the BBG controller called and asked Mr. Hobbs if he had watched the aircraft land at BBG. Mr. Hobbs advised that he had observed SWA4013 until about Point Lookout, which is a reference point for PLK, approximately about 6 miles from BBG." Next, the tower controller failed to mitigate the incorrect runway landing after giving clearance to land. Automation support mitigation was ineffective due to the radar floor in the local area rendering the MSAW alert unusable for the situation. In addition, the crew continued with poor SA until touchdown, using their navigational aids ineffectively, and due to night conditions, VLO proved ineffective.

Case Number: 21
NTSB Accident Number: ERA14FA192
Date: 11 April 2014

Summary: A comprehension failure caused a controller to become diverged in the pilot's spatial orientation state, contributing to a loss of control and terrain impact.

Synopsis: A single-engine Piper PA-32RT (N39965) pilot experienced spatial disorientation near Hugheston, WV. Combined with a controller's unknown and later known divergence and the resulting actions, the pilot's spatial disorientation resulted in loss of aircraft control and subsequent terrain impact, killing two on board. The flight was operating during day IMC under IFR under CFR Part 91, taking off from Akron, OH and flying to Spartanburg, SC. At the time of the accident, the pilot was receiving radar vectors from Indianapolis Center. During the course of the events, the pilot exhibited symptoms of spatial disorientation, including altitude and heading deviations along with missed and slurred communications. However, the center controller did not feel the situation was an emergency. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report and Communication Transcripts.

Table D-21. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Ambiguous observations, Expectation-driven comprehension bias, and incorrect knowledge	Inference – Ambiguity Resolution Integration	Comprehension	Pilot spatial orientation	Incorrect (vectors to mitigate)	Known divergence (TDS & voice observable)	None	Terrain impact (loss of control)

Divergence state: The approach controller experienced unknown divergence based on controller testimony stating he did not feel it was an emergency. Controller testimony in the NTSB ATC Group Chairman's Factual Report stated "he had not considered the situation to be an emergency until the pilot no longer responded to transmissions followed by the loss of radar contact," which occurred at the time of terrain impact, some 20 minutes after the first potential indications of spatial disorientation. The diverged state was determined to be the current pilot state of spatial orientation (or disorientation).

Divergence causes: Although the controller showed evidence of awareness of an off-nominal situation, it appears he determined the accident aircraft was attempting to "pick through" the weather using real-time data he thought was on board the aircraft. This divergence in the current pilot state likely occurred due to an integration failure in the comprehension process. The controller received several ambiguous observations from the TSD consisting of numerous deviations from course. This may have combined with expectation-driven comprehension bias regarding his assumption of an onboard weather radar. For instance, the D-side controller stated "he thought the pilot was climbing and descending in order to avoid weather." The NTSB stated "it is likely that, based on the pilot's use of the word 'radar,' the controller assumed that the airplane was equipped with airborne weather radar." Ambiguous observations combined with expectation-driven comprehension bias may have led to the controller inferring the pilot was avoiding heavier areas of precipitation during his flight, rather than maneuvering erratically due to spatial disorientation. Next, the pilot began missing radio calls from the controller. According to the NTSB, after the initial indications of altitude deviations, the controller queried the pilot four times and only responded once, with slurred speech and decreased speech rate. The incorrect inference, combined with missed and slurred pilot communications and lack of knowledge regarding spatial disorientation cues led to an integration failure of multiple observations of the state of the pilot.

Divergence consequences: Once diverged, the controller failed to mitigate the pilot spatial disorientation (potentially hazardous consequence). However, there was evidence of known divergence during the incident. The controller asked the pilot if he required assistance a total of 8 times over 15 minutes, signifying he understood the pilot was having some difficulties with the flight. However, the controller failed to transition to re-convergence and understand both the nature of the emergency or the seriousness of the emergency. According to the NTSB, the controller "failed to notify his supervisor of the situation … failed to ask specific questions to fully understand the difficulties the pilot was experiencing, and finally, he did not declare an emergency on behalf of the pilot, which would have ensured that the airplane was given priority handling." The consequence of divergence was initially the lack of an emergency declared or considered which may have given the aircraft priority handling and different service. In fact, the Front Line Manager (FLM) stated that "she did not recall anybody discussing or considering declaring an emergency on behalf of the pilot." However, continued heading and altitude deviations and missed communications eventually led to the controller transition to known divergence as described earlier. Yet due to the incorrect state awareness, the controller continued attempting to vector the pilot away from heavy precipitation rather than in VMC. Finally, the controller's supervisor (FLM) was finally aware of a situation developing, but appears to have been divergent as well. According to the NTSB, "the supervisor only monitored the situation momentarily before returning to her desk." The controller failed to re-converge and the pilot eventually lost control of the aircraft, ending with terrain impact.

Case Number: 22
NTSB Accident Number: OPS14IA005
Date: 24 April, 2014

Summary: A projection failure caused a controller to become diverged in an aircraft's future position, contributing to a NMAC.

Synopsis: A tower controller's unknown divergence contributed to an Embraer ERJ145 and a B-737 experiencing a NMAC at the Newark Liberty International Airport (EWR), Newark, NJ, during daylight hours. Both aircraft were operating on IFR flight plans and receiving sequencing services from EWR Local Control (LC) during the incident, and both were operating under CFR Part 121. The ERJ145 (ASQ4100) was given takeoff clearance on runway 4R as the B737 (UAL1243) was on final for landing to the crossing runway 29. The controller anticipated enough separation for the departing ERJ145 before the B737 would land. However, the controller subsequently commanded the B737 to go-around while the ERJ145 was on takeoff roll. The crew of each aircraft obtained visual of one another and the B737 flew over the ERJ145 by approximately 400 feet, resulting in a NMAC. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB docket, including the ATC Group Chairman's Factual Report, 5 Controller Personnel Statements, and 3 Pilot Personnel Statements. Figure D-17 shows a radar graphic illustrating the flight paths of ASQ4100 (ERJ145) and UAL1243 (B737) as they cross over the intersection of runways 4R and 29.

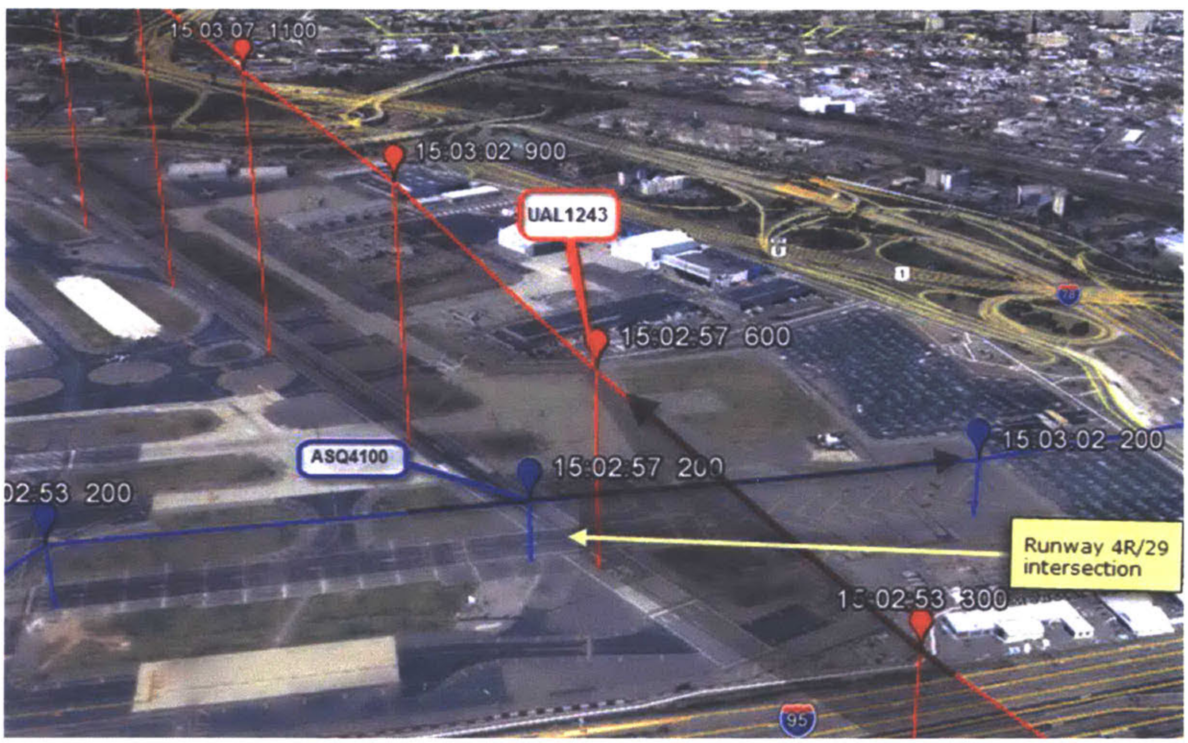

Figure D-17. Radar graphic illustrating the flight paths of ASQ4100 (ERJ145) and UAL1243 (B737).

Table D-22. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Incorrect knowledge	Projection	Future aircraft position → Future aircraft separation	Incorrect (cleared ERJ145 for takeoff)	Re-convergence (monitoring) / Recovery action (commanding go-around)	VLO	NMAC

Divergence state: The controller experienced unknown divergence during the incident. Evidence of unknown divergence was based on a possible unanticipated safety alert (ASDE-X), unanticipated violation of separation (NMAC) while both aircraft were following ATC commands, controller and pilot testimony of incongruent state awareness, and a controller non-conservative control strategy. Although the ASDE-X alerted during the incident, it is not apparent that the controller heard the ASDE-X or experienced re-convergence due to the ASDE-X, as it happened near-simultaneously with the controller commanding the B-737 to go-around. However, both aircraft were following ATC instructions, yet there was a NMAC during their takeoff and landing operations respectively. The controller stated in testimony that he "did not send UAL1243 around early enough" or "he should not have provided ASQ4100 a takeoff clearance at all," signifying a lack of awareness of their future separation at the time of the incident. In addition, one of the pilots of the B737 stated "we heard the tower clear an aircraft for takeoff on runway 4. I thought at the time that we were kind of close for a departure ahead of us." This signifies the pilot's projection of an uncertain separation state between the two aircraft, which was corroborated when the crew "elected, as tower was directing, a go-around." Finally, the Cab Coordinator stated he "recalled thinking that it was going to be close" when witnessing the takeoff clearance, signifying a non-conservative controller strategy during the incident. It appears the controller experienced divergence in the future separation state between the two aircraft stemming from divergence in the future position state of the ERJ145 departing the runway.

Divergence causes: This future projection appears to have diverged due to incorrect knowledge input to the mental model of the projection process. The controller appeared to have assumed a quicker response time between ASQ4100 receiving the takeoff clearance and beginning their takeoff roll. According to NTSB testimony, the controller stated that when he looked back to the departure end of runway 4R after providing clearance, "he noticed ASQ4100 was not rolling and saw UAL1243 turning base to final. Then he instructed UAL1243 to go-around." In addition, when recalling the incident, the Cab Coordinator said "the LC controller cleared ASQ4100 for takeoff; however, the pilot did not commence his takeoff roll right away." In fact, the Operations Supervisor in Charge stated "but the root cause of that event was the failure of the ASQ4100 pilot to roll in a timely manner." Accounting for the correct time delay between receiving takeoff clearance and beginning the takeoff roll may have produced a more consistent future position of the ERJ145 and a consistent future separation state between the ERJ145 and B737, possibly leading the controller to not attempt the ERJ145 takeoff given the spacing.

Divergence consequences: Once diverged, the controller cleared the ERJ145 for takeoff (hazardous action – incorrect action) contributing to an aircraft-to-aircraft conflict (potentially hazardous situation). However, the controller experienced re-convergence during the incident. Evidence of re-convergence was based on updated observables when the controller witnessed the ERJ145 not taking off as expected. In addition, this led to a subsequent command to resolve the situation by commanding a 'go-around' to the B737 and traffic alerts to both aircraft. Finally, the controller testified he "noticed ASQ4100 was not rolling and saw UAL1243 turning base to final. Then he instructed UAL1243 to go-around." The crew in both aircraft had effective VLO which enabled a NMAC to occur rather than a MAC.

Thesis Case Number: 23
Date: 15 August, 2014
NTSB Accident Number: OPS14IA011

Summary: A working memory failure caused the controller to become diverged in the existence of CAL5254, which contributed to a LoSS between two aircraft.

Synopsis: A controller's unknown divergence contributed to a LoSS between a B-777 (AAL 183) and B-747 (CAL5254) while enroute near Shemya, Alaska. Both aircraft were operating on IFR flight plans and receiving separation services from Anchorage Center during their night flights. AAL183 was flying west southwest bound at FL360 while KAL035 and CAL5254 were flying northeast bound at FL370 on a crossing route. AAL183 requested a climb to FL370 and the controller granted the request after AAL183 passed the flight path of KAL035, creating a conflict between AAL183 and CAL5254. Figure D-18 shows the screen capture of the Ocean21 display at the approximate time of AAL183's clearance to climb to FL370 upon passing KAL035. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, NTSB Aviation Incident Final Report, and NTSB docket, including the ATC Group Chairman's Factual report and ATC Systems Service Review.

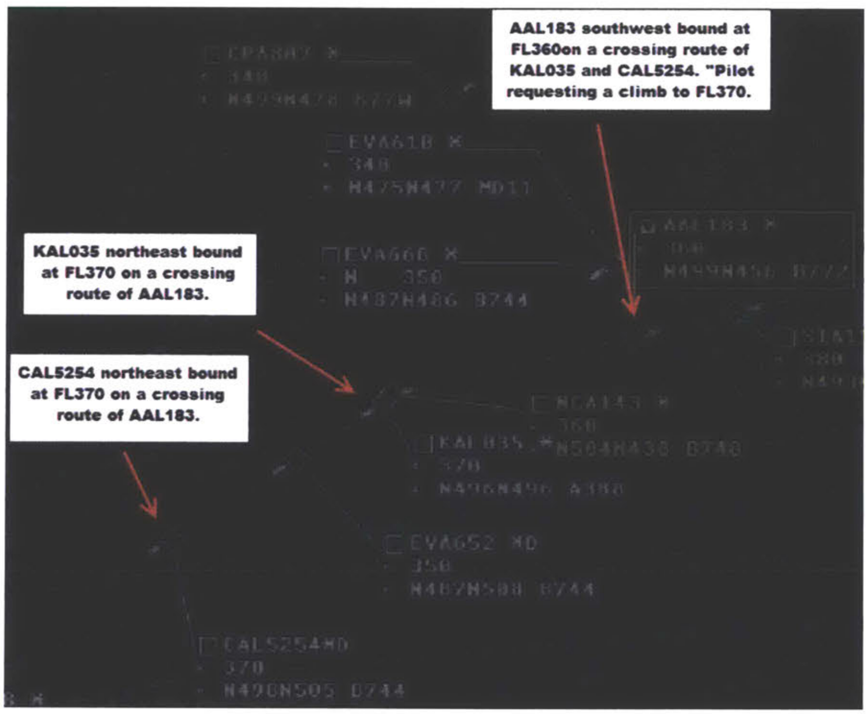

Figure D-18. Screen capture of the Ocean21 display at the approximate time of AAL183 clearance to climb.

Table D-23. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Working memory failure	Comprehension process	Aircraft existence → Future aircraft separation	Incorrect (granted climb request)	Re-convergence (STCA) / No recovery action	TCAS RAs in CAL5254 and AAL183	LoSS

Divergence State: The controller experienced unknown divergence. Evidence of unknown divergence was based on controller testimony of inconsistent state awareness. The controller testified that he "didn't see CAL5254 when climbing AAL183 to FL370." It appears the controller originally experienced unknown divergence in the existence of CAL5254. Interestingly, the original divergence was found to be inconsequential due to the lack of a consequential situation. Before the request to climb to FL270 by AAL183, there was no conflicting traffic for CAL5254. However, after the climb request was made, the divergence became consequential based on the consequential situation developing from conflicting traffic (CAL5254) at the requested climb altitude of AAL183. Therefore, the diverged state propagated to divergence in the future position state of CAL5254 and the future separation state between CAL5254 and AAL183.

Divergence Causes: The existence of CAL5254 likely diverged due to a working memory failure. Exactly 3 minutes before AAL183's climb request, the controller had communicated with CAL5254. However, when asked why he missed CAL5254 during the resultant event, the controller stated he "just missed it." There was not enough evidence to determine the working memory failure cause. After some time, a request was made from AAL183 to climb. Here, the working memory failure combined with two instances of perception process failures that failed to mitigate the original divergence. The first failed perception process was due to a lack of perception of the observable of CAL5254 on the Ocean21 display. The cause of this perception failure is unknown. The NTSB stated "he [controller] looked for opposite direction traffic and saw KAL035 as a potential conflict…. but did not look past KAL035 for any other possible conflicts." The second failed perception process was due to a lack of an observable, an extended conflict probe which was inhibited due to system policies. This extended conflict probe had been inhibited by the organization due to a high false-alarm rate. Therefore, the combined working memory and perception failures continued the unknown divergence.

Divergence Consequences: The consequential divergence manifested itself by the controller granting the climb request, which was an incorrect action, and led to the potentially hazardous state of an aircraft-to-aircraft conflict between CAL5254 and AAL183. However, before the hazardous consequence occurred, there was evidence of an immediate re-convergence. The controller received an unanticipated STCA. The STCA warned the controller of an impending LoSS and the NTSB investigation illustrated the controller perceived and comprehended the STCA immediately, stating that "when the conflict alert initiated, Mr. Coleman realized that he had a loss of separation. He wanted to communicate with AAL183 and descend the flight to FL360 immediately." However, based on a late STCA alert, controller task prioritization and execution, along with a lack of aircraft communication replies, the controller failed to resolve the potentially hazardous state with a correct recovery action. Yet TCAS RAs in both cockpits provided for effective system mitigations to result in a LoSS as the hazardous consequence versus a MAC or NMAC.

Case Number: 24
NTSB Accident Number: ERA15FA025
Date: 23 October, 2014

Summary: A projection failure caused a tower controller to become diverged in an aircraft's future position, contributing to a MAC.

Synopsis: A tower controller's unknown divergence contributed to a Cirrus SR22 (N122ES) colliding with a Robinson R44 helicopter (N7518Q) approximately 1 mile southwest of the Frederick Municipal Airport, Frederick, Maryland. Both flights were operating during day VMC conditions. N122ES was operating on an IFR flight plan and N7518Q as operating VFR, both under CFR Part 91. At the time of the accident, both pilots were receiving tower services from the tower controller located at the field. N122ES reported 10 miles west of the field at 3,000 feet. The controller requested N122ES report 3 miles west for Runway 30. Approximately 40 seconds later, the controller cleared N7518Q for takeoff to remain in the pattern. When N122ES reported 3 miles west, the controller was working the ground frequency with a business jet. Thirty (30) seconds later, the controller instructed N122ES to a left midfield downwind for runway 30 and alerted him for "3 helos below ya in pattern." The pilot of N122ES acknowledged and reported 2 of the helos in sight. The controller said he had N122ES in sight and to "maintain altitude until base." Seven (7) seconds later the MAC occurred. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, two ATC radar plots, Witness Statements and Interview Summaries, Controller Personal Statements, and modifications to the factual report. Figure D-19 shows the ground track of the Cirrus aircraft during the accident.

Figure D-19. Ground track of the Cirrus during the accident.

Table D-24. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Unknown	Incorrect knowledge	Projection	Future aircraft position → Future aircraft separation	Incorrect (cleared N7518Q takeoff)	None	None	MAC

Divergence state: The tower controller experienced unknown divergence based on evidence of an accident without controller awareness, controller testimony of incongruent state awareness versus the actual system, and controller/pilot miscommunication. For example, the NTSB ATC Group Chairman's Factual Report stated "The local controller then turned to break off the aircraft that was on approach to runway 23, when Ms. Salcedo heard screaming over the frequency and immediately looked back and seen the Cirrus falling from the sky." In addition, the controller stated, "If she had known that the Cirrus was so close when she cleared N7518Q, she would have held off on giving N7518Q the departure clearance until she observed that the Cirrus was clear." Finally, the NTSB synopsis stated that "When the accident airplane was 3 miles from the airport, the pilot reported the airplane's position to the controller, but the controller missed the call because she was preoccupied with the clearance read-back from the business jet pilot." It appears the future separation state between N122ES and N7518Q potentially diverged due to future position state projection of the N122ES diverging.

Divergence causes: This state diverged most likely due to a mental simulation failure within the projection process. As the NTSB Group Chairman's Factual Report state, "she recalled that the Cirrus was closer than she expected" and the controller testified "If she had known that the Cirrus was so close when she cleared N7518Q, she would have held off on giving N7518Q the departure clearance until she observed that the Cirrus was clear." The mental simulation failure may have occurred due to a reliance on default values in the comprehension process, specifically the velocity of the Cirrus. However, there was no evidence to determine the cause of the mental simulation failure.

Divergence consequences: Once diverged, the controller cleared N7518Q for takeoff (hazardous action – incorrect action), leading to an aircraft-to-aircraft conflict (potentially hazardous situation). There was no evidence of known divergence or re-convergence before the accident. The conflict was also due to altitude errors by both pilots. The NTSB synopsis stated "contributing to the accident were the airplane pilot's descent below the published airplane traffic pattern altitude (TPA) and the helicopter pilot's climb above the proper helicopter TPA," which the latter was influenced by "the lack of a published helicopter TPA." However, the consequence of this divergence could have been mitigated with an updated projection of future position, which did not occur due to a lack of observable (no radar in the control tower) and a barrier to an observable (the lack of the "3 mile" report call). According to NTSB testimony, the controller stated "that she never received the 3-mile call that she had requested" and "she wished she would have received the three-mile call from the Cirrus, and since she had not, felt like she had more time and therefore did not issue the fixed wing traffic to the helicopter, and assumed they would never have been a factor." The controller did not receive the three-mile call due to communicating with another aircraft at the time, causing a stepped-on radio call. This barrier to the observable may have been due to poor attention allocation causing poor information sampling; however, there was no evidence of this cause. After clearing N7518Q for takeoff, the controller communicated with another aircraft for 43 seconds to issue a clearance, cutting out communication on the other frequency. In addition, the TCAS in N122ES was ineffective due to being inhibited with flaps down and neither pilot executed proper VLO.

Case Number: 25
NTSB Accident Number: ERA15MA259
Date: 7 July, 2015

Summary: A perception and comprehension failure causes an approach controller to become diverged in a pilot's intent, followed by a projection failure causing the same controller to become diverged in a different aircraft's future position, contributing to a MAC.

Synopsis: An approach controller's unknown divergence contributed to a MAC between a C-150 (N3601V) and an F-16, over Moncks Corner, SC. The F-16 was operating on an IFR flight plan in contact with and receiving radar vectors from approach control while practicing an instrument approach at Charleston AFB. The C-150 was conducting a personal flight operating day VFR under CFR Part 91 and was not in contact with ATC services at the time of the accident. The F-16 was preparing to fly an instrument approach during day VMC at Charleston Air Force Base under radar vectors of approach control. While level at 1,600 feet MSL, the controller witnessed the C-150 depart a nearby airport on her display, but thought the aircraft would remain in the local traffic pattern. When the two aircraft were within 3.5 nm and 400 feet vertically from one another, the controller notified the F-16 pilot of the traffic by issuing a traffic advisory (40 seconds before the collision). Ten (10) seconds later, the controller advised the F-16 pilot to turn left heading 180 if traffic was not in sight, then 8 seconds later a turn left immediately. The F-16 pilot began a standard rate turn to the left, colliding with the C-150 20 seconds later. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, Operational Factors Group Chairman's Factual Report, Human Performance Specialist's Factual Report, and Controller Interview Summary. Figure D-20 shows the ground tracks of the aircraft during the accident.

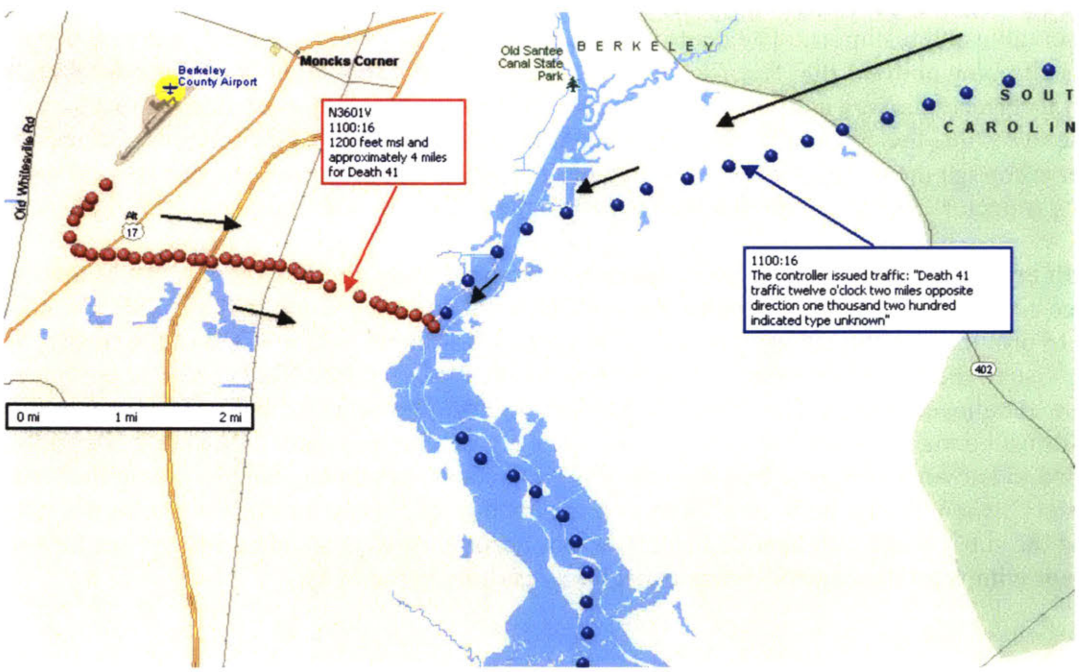

Figure D-20. Ground tracks of both accident aircraft, F-16 (blue) and C-150 (red).

Table D-25. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
System policy	Lack of observable	Perception	Pilot intent → Future aircraft separation	No action (to mitigate)	Re-convergence (due to TSD) / Incorrect recovery action	None	MAC
Expectation-driven comprehension bias	Inference - Guessing	Comprehension					
Unknown	Incorrect knowledge	Projection	Future aircraft position → Future aircraft separation	Incorrect action (to mitigate)	None		

First divergence and re-convergence: The controller experienced unknown divergence based on an unacknowledged safety alert and controller testimony. Although the controller stated she didn't hear the CA, she communicated the traffic advisory to the F-16 pilot 3 seconds after it alerted. In addition, the controller stated she "noticed an aircraft depart from MKS and initially thought the aircraft at MKS was in the local VFR pattern." It appears the first diverged state was the C-150's current intent state, which led to the divergence in the future separation state of the two aircraft. According to testimony, the controller "thought the aircraft at MKS was in the local VFR pattern." The divergence potentially occurred due to the ambiguous observation of the aircraft climbing, which looked similar to climbing in the pattern. In addition, there was a lack of observable of the aircraft's intent based on flying VFR without a flight plan or flight following. Lastly, there may have been an expectation-driven comprehension bias of the C-150's intent. The controller stated "pattern traffic at MKS was rare and typically stayed below 1,000 feet."

The divergence led the controller to no action (hazardous action) to mitigate the already developed aircraft-to-aircraft conflict (potentially hazardous situation). The controller appeared to re-converge based on an observable and testimony. The controller stated "she noticed that the aircraft that had departed MKS was climbing above 1,000 feet," leading to her call to the F-16 pilot in an attempt for them to gain visual, an incorrect recovery action based on the second divergence. However, this led to a short timeframe to resolve the conflict. In fact, the CA alarmed 24 seconds after the aircraft climbed above 1,000 feet, although the controller testified she didn't hear the CA. However, she understood the conflicting trajectory and transmitted a traffic alert to the F-16 pilot within 3 seconds of the CA.

Second divergence: After the controller understood the impending conflict, there was a second unknown divergence sequence based on the resulting controller testimony. According to the NTSB, the controller's plan was to provide a traffic advisory to the F-16 pilot so they could obtain visual of the traffic. Without acquiring visual, the controller vectored the F-16 in front of the C-150 traffic in order to continue the approach and believed this could maintain separation because she believed the F-16 pilot would perform a high-performance maneuver and that fighter airplanes could 'turn on a dime.' The controller potentially transitioned to known divergence based on the observable and her strategy change, using the term 'immediately' when telling the F-16 pilot to turn to heading 180. However, the F-16 pilot did not attain visual and the subsequent commanded maneuver was accomplished at standard instrument turn rates, inconsistent with what the controller was expecting, resulting in the MAC.

Case Number: 26
NTSB Accident Number: WPR15MA243
Date: 16 August, 2015

Summary: A working memory failure caused a tower controller to become diverged in an aircraft's identity, contributing to a MAC.

Synopsis: A tower controller's potential unknown divergence contributed to a MAC between a C-172 (N1285U) and a Sabreliner 60 (Eagle 1), approximately 1-mile northeast of Brown Field Municipal Airport (SDM), San Diego, CA while in the traffic pattern. The flights were operating during day VMC under VFR and CFR Part 91. At the time of the incident, the pilots were receiving sequencing services from the tower controller located on the field. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, and the Human Performance Specialist's Factual Report. Figure D-21 shows the ground tracks of the aircraft just before the accident.

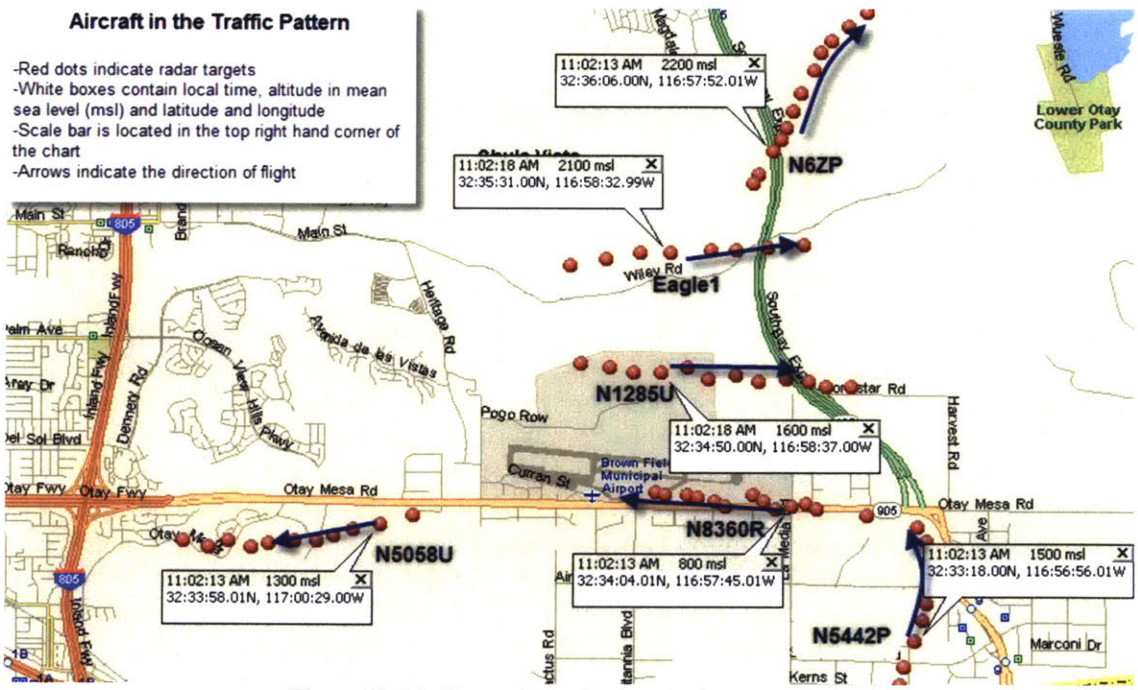

Figure D-21. Ground tracks just before accident.

Table D-26. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Stress	Working memory	Comprehension	Aircraft identity → Future aircraft separation	Incorrect (cleared Eagle 1 to turn base)	Known divergence (window)	None	NMAC

Divergence state: The tower controller apparently experienced unknown divergence based on an accident occurring due to executed controller sequencing, controller testimony of incongruent state awareness versus actual system state, and controller miscommunication. According to the NTSB report,

> The local controller stated in his interview that he saw Eagle1 flanked by a pair of Cessnas when the pilot reported that he was, "...abeam and had the traffic to the left and right in sight." The

> local controller believed that the Cessna on the close in right downwind [to the right of Eagle1] was N6ZP, but it was actually N1285U. The local controller stated that he issued the pilot of N6ZP a right 360-degree turn in order for him to rejoin the midfield downwind and resolve the conflict with Eagle1. He felt that the right turn would help the Cessna avoid Eagle1's wake turbulence.
>
> When N6ZP acknowledged the right 360-degree turn instruction, the local controller stated that in his mind, the Cessna on the right downwind [to the right of Eagle1] had received the instructions and the conflict with Eagle1 would be resolved. Anticipating that the Cessna to the right of Eagle1, on the right downwind at 1,500 feet, would be making a right 360-degree turn, the local controller instructed Eagle1 to turn base, and cleared Eagle1 to land on runway 26R.

It appears the diverged state was the N1285U's identity, which led to a divergence in the future position projection of the N1285U and therefore the future separation state of N1285U and Eagle 1. According to testimony, the controller knew he had a conflict between N1285U and Eagle 1 to resolve when taking over from the trainee. The NTSB report stated, "Mr. Hill recalled that he had four immediate issues to resolve: ... (4) The potential conflict between Eagle1 and N1285U." To resolve the conflict, the controller planned to give N1285U a right 360-degree turn as stated above.

Divergence causes: The controller divergence of N1285U's identity was most likely due to a working memory failure due to excessive workload. According to the NTSB Synopsis, "As a result of the high workload, the LC made several errors after taking over the position from the LC trainee." This, coupled with ambiguous observables of two C-172s in the pattern, led to the controller provides sequencing instructions for Eagle 1 to turn base.

Divergence consequences: Once diverged, the controller cleared Eagle 1 to turn base (hazardous action – incorrect action) creating an aircraft-to-aircraft conflict (potentially hazardous situation). When N6ZP responded to the turn call, the expectation bias from the controller in combination with a lack of perception of the aircraft's turn led to the controller clearing Eagle 1 to turn base. The lack of perception was possibly due to high workload. The NTSB synopsis stated that at the time of the accident, the controller was managing nine aircraft, although in testimony his personal limit was seven. This may have led to poor attention allocation and therefore poor information sampling. There was evidence of known divergence immediately before the accident due to an observable combined with pilot confirming communication. According to the NTSB full narrative, the controller "looked to ensure that Eagle 1 was turning as instructed and noticed that the Cessna on the right downwind ... had not begun the 360° turn." Next, the NTSB stated "At 1103:08, the local controller asked the pilot of N1285U, 'Are you still on downwind sir right downwind'." This occurred moments before the accident. There was no evidence of re-convergence until observation of the accident. The aircrew of Eagle 1 also failed to maintain visual on N1285U.

Case Number: 27
NTSB Accident Number: ERA15FA340
Date: 7 September, 2015

Summary: Perception and comprehension failures caused a controller to become diverged in the pilot's spatial orientation state, contributing to a loss of control and terrain impact.

Synopsis: A single-engine Beechcraft A36 (N36HT) pilot experienced spatial disorientation near Kernersville, North Carolina. Combined with a controller's unknown divergence and the resulting actions, the pilot's spatial disorientation resulted in loss of aircraft control, subsequent aerodynamic stall/spin, and terrain impact, killing all three onboard. The flight was operating during day IMC under IFR under CFR Part 91, taking off from Sarasota, Florida and flying to Greensboro, North Carolina. At the time of the accident, the pilot was receiving radar vectors from Greensboro Approach Control. During the course of the events, the pilot exhibited symptoms of spatial disorientation, including missed communication, agitation, and confusion, along with sporadic heading and altitude control. However, the approach controller did not feel the situation was an emergency and commanded multiple heading and course reversals, along with 'no-gyro' vectors, possibly exacerbating the pilot's spatial disorientation. Data was obtained from the NTSB Synopsis, NTSB Full Narrative, and NTSB Docket, including the ATC Group Chairman's Factual Report, ATC Group Chairman's Revised Factual Report, and Personal Statements from Witnesses and previous Flight Instructors. Figure D-22 shows the ground track of the accident aircraft just before the accident.

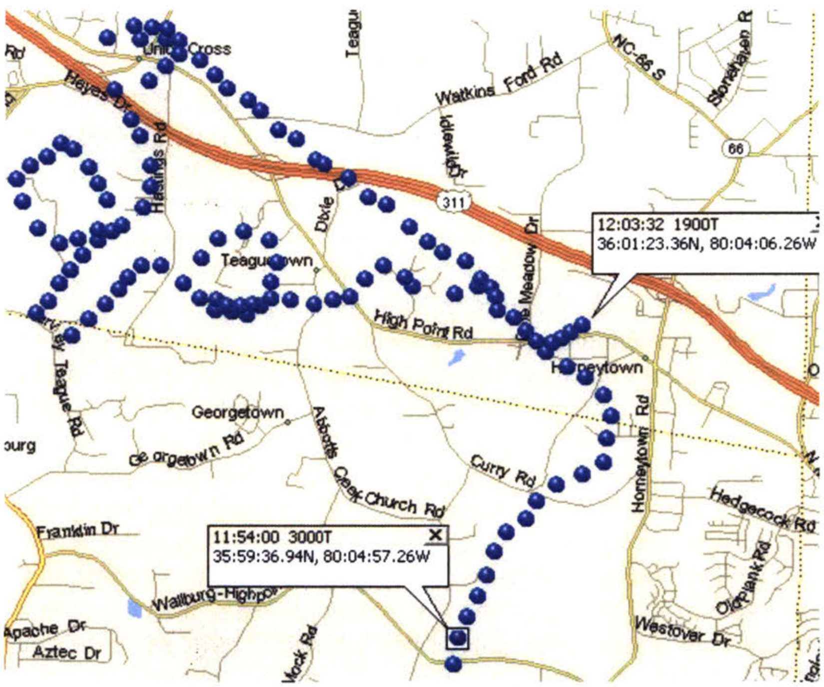

Figure D-22. Ground track just before the accident.

Table D-27. Divergence causes and consequences.

Mechanism of Divergence	Source of Divergence	Process Failure	Diverged State (Original and Final)	Hazardous Action	Transition	System Mitigation	Hazardous Consequence
Indiscriminate observable	Lack of perception	Perception	Pilot spatial orientation	Incorrect (poor vector to mitigate)	Known divergence (normal scan) / Re-convergence (pilot communication) / No recovery action	None	Terrain impact (loss of control)
Incorrect knowledge & expectation-driven comprehension bias	Integration	Comprehension					

Divergence state: The approach controller experienced unknown divergence based on evidence of altitude and heading violations without controller awareness of an emergency state, controller testimony stating he did not feel it was an emergency, miscommunication between the pilot and controller, communication regarding flight safety from another controller, and non-conservative controller strategies and commands. Most significant, controller testimony in the NTSB ATC Group Chairman's Factual Report stated "he thought N36HT was a priority but not an emergency." Also, during the end of the event another controller told the approach controller "that the cloud tops in the area were 3600 feet," signifying a possible recommendation to climb the aircraft to VMC. Finally, no-gyro vectors were not appropriate for this type of situation and may have exacerbated the spatial disorientation. However, the controller still felt like the situation did not warrant an emergency classification. The diverged state was determined to be the pilot state of spatial disorientation. Although the controller indicated knowledge of an off-nominal situation, he determined the accident aircraft was a priority but not an emergency, which may have led to different actions on the part of the controller.

Divergence causes: The divergence likely occurred due to an integration failure in the comprehension process. The controller received several observations that when combined signified an emergency situation. First, when initially vectoring the aircraft to ILS final, the pilot asked how his tracked looked, which the controller determined was not a common question from a pilot on a precision approach. Second, the aircraft flew through the final approach course. Third, the pilot did not maneuver following the subsequent vector to final. Fourth, the pilot failed to maneuver to another heading shortly following the cancelled approach clearance. Fifth, the pilot failed to turn again following another vector and subsequently failed to respond to numerous communications. These, combined with the pilot failing to fly assigned altitudes should have led to the controller assuming the aircraft was an emergency and the pilot was spatially disoriented. This failed comprehension process was likely due to a lack of or incorrect knowledge on the recognition of such an emergency, which was a contributing factor to the accident according to the NTSB, which stated "contributing to the accident was deficient Federal Aviation Administration air traffic control training on recognition and handling of emergencies." Also, expectation-driven comprehension bias may have played a role as the controller stated "if an instrument-rated pilot was flying in IFR conditions, he [controller] expected the pilot to comply with ATC instructions and tell him [controller] if something was wrong." Finally, an indiscriminate observable of the trajectory of the aircraft could have propagated from a perception failure to the comprehension failure. According to the NTSB ATC Group Chairman's Factual Report, the controller could not tell the aircraft was flying in circles due to personal preferences were at the furthest allowable setting to allow him to see additional aircraft. This may have provided additional insight to the state of the aircraft.

Divergence consequences: Once diverged, the controller executed poor vectoring (hazardous action – incorrect action) that failed to mitigate the potentially hazardous situation that had developed of pilot spatial disorientation. The NTSB synopsis stated "once the pilot began the higher workload phase of flight preparing to execute the instrument landing system (ILS) approach in actual instrument meteorological conditions, he began to exhibit some uncertainty and confusion." In addition, the NTSB full narrative stated his instructor had told him "not to fly in actual IFR conditions until he gained more flight experience." The spatial disorientation combined with apparent unknown divergence of the pilot orientation led to multiple vectors in both directions, possibly exacerbating the spatial disorientation of the pilot. However, the controller could have transition to re-convergence following the pilot's communication "we are almost disoriented" and the controller stated he "heard the pilot say that he was getting disoriented, and detected a change in his voice." However, this ambiguous observable, combined with the previous expectation-driven comprehension bias contributed to a continued incorrect inference of the pilot's state of spatial disorientation. The resulting action from this additional observable was to elicit information as to whether the pilot could accept no-gyro vectors, which are not considered appropriate for this type of emergency. When combined with the incorrect knowledge of the reasons to execute no-gyro vectors and poor front line manager supervision led to the execution of no-gyro vectors. These no-gyro vectors may have exacerbated the pilot's spatial disorientation even more, leading to a loss of aircraft control, aerodynamic stall/spin, and impact with the surrounding terrain. The controller's strategy later changed to attempting to climb the aircraft to VMC, providing possible evidence of re-convergence right before the accident.

Appendix E: Field Study Focused Interview Questions

Demographic Questions

1. What is your name?
2. What is your age?
3. What is your gender?
4. What facility do you control from?
5. What is your position or job title?
6. How many years'/months' experience do you have as an ATC controller?
7. What ATC certifications do you possess?
8. How many years'/months' experience do you have controlling unmanned aircraft?
9. What type of unmanned aircraft have you controlled?
10. What other bases have you controlled unmanned aircraft from?
11. Have you controlled unmanned aircraft deployed?
12. What types of aircraft do you control here?

Background and Training

1. What differences were you trained on with respect to unmanned aircraft versus manned aircraft?

Policies and Procedures

1. What are your standard procedures for controlling unmanned aircraft?
   After the initial response, ask these follow-up questions if not cited previously.
   A. Do you give operational priority to manned or unmanned aircraft over the other?
   B. Do you consider right-of-way rules between manned and unmanned aircraft when controlling?
   C. Do you have policies for maneuvering a manned or an unmanned aircraft instead of the other to maintain separation, yes or no? Avoid a collision, yes or no?
   D. Are restrictions imposed on unmanned aircraft in the airspace you control, yes or no?
      i. If yes, can you explain what these restrictions are? (Weather, Airspace, Populated areas, Integration with other aircraft)
   E. Do you give traffic callouts to unmanned aircraft?
      i. What do you expect unmanned aircraft operators to do with that information?
   F. What off-nominal procedures for unmanned aircraft do you have?

2. How do unmanned aircraft operations integrate with manned aircraft operations here?
   After the initial response, ask these follow-up questions if not cited previously.
   A. Do you use segregation to separate manned and unmanned aircraft, yes or no?
      i. If yes, what type of segregation do you use?
   B. Do you give unmanned aircraft additional spacing for separation services, yes or no?
      i. If yes, what amount of spacing do you give them?

Manned Aircraft and Unmanned Aircraft Differences

1. Do you consciously distinguish, or keep track, if an aircraft is manned or unmanned, yes or no?
   A. If yes, how do you know if an aircraft is manned or unmanned?
      i. Do you use flight plans to distinguish between manned and unmanned aircraft?
      ii. Do you use your displays to distinguish between manned and unmanned aircraft?

        iii. Do you use communication to distinguish between manned and unmanned aircraft?
    B. If no, do you distinguish between any types of aircraft for your control strategies?

2. What differences do you think about or consider between manned and unmanned aircraft when controlling them?

After the initial response, ask these follow-up questions if not cited previously.

- A. Do you consider differences in the speed of response between manned and unmanned aircraft, yes or no?
    - i. If yes, are there types of clearances you can't give unmanned aircraft?
    - ii. If no, do you recognize a difference in the speed of response between manned and unmanned aircraft, yes or no?
- B. Do you consider maneuver performance differences between manned and unmanned aircraft, yes or no?
    - i. If yes, what types of performance differences do you consider?
        1. Climb rate?
        2. Descent rate?
        3. Turn rate?
        4. Min/Max speed?
        5. Loiter capability?
        6. Size?
        7. Weight?
        8. Wake turbulence?
    - ii. Can you rank order these?
- C. Do you consider communication reliability differences between manned and unmanned aircraft, yes or no?
    - i. Do you find that one category of aircraft has more or less intermittency issues than the other?
    - ii. Do you find that one category of aircraft responds to radio calls more or less often than the other?
    - iii. Do you receive the same amount of prosodic information from manned versus unmanned aircraft?
- D. Are there similar differences among different manned aircraft types compared to the differences we have just discussed between manned and unmanned aircraft, yes or no?
- E. Are there similar differences among different unmanned aircraft types compared to the differences we have just discussed between manned and unmanned aircraft, yes or no?
- F. Do you consider right-of-way rules, yes or no? Operational priorities, yes or no?
- G. Do you consider the type of communication link, yes or no?
- H. Do you consider the possibility of alternate communication, yes or no?
- I. Do you consider the possibility of lost link on unmanned aircraft, yes or no?
- J. Do you consider the lack of a see-and-avoid capability on unmanned aircraft, yes or no?
- K. What do you think are the most important differences between manned and unmanned aircraft?
    - i. Could you rank these differences 1-5? Procedural difference? Restriction differences?
    - ii. Why do you think considering these differences are important?
    - iii. What do you think are the most important differences between any types of aircraft? (manned or unmanned)
        1. Could you rank these differences 1-5?
        2. Why do you think considering these differences are important?

3. Do you have different control strategies for unmanned aircraft compared to manned aircraft, yes or no?

A. If yes, can you describe how you control unmanned aircraft differently than manned aircraft?
   After the initial response, ask these follow-up questions if not cited previously.
   i. Do you pay more, less, or the same amount of attention to unmanned aircraft compared to manned aircraft? Change how you control?
   ii. Does your workload increase, decrease, or remain the same when controlling unmanned aircraft? Change how you control?
   iii. Do you find yourself more proactive, reactive or the same when controlling unmanned aircraft compared to controlling manned aircraft? Change how you control?
   iv. Do you segregate unmanned aircraft from manned aircraft more frequently than other categories or types of aircraft?

B. If no, do any of the differences cited in Question 2 (this section) affect your control of unmanned aircraft?

C. Do your control strategies change if a manned or unmanned aircraft are in airspace together or in proximity to each other, rather than being geographically segregated?

4. How do you think about, or project, unmanned aircraft behavior in the future compared to how you think about, or project, manned aircraft behavior in the future?

After the initial response, ask these follow-up questions if not cited previously.

A. Do you find that you are able to anticipate actions of unmanned aircraft more reliably, less reliably, or neutral compared to manned aircraft?
   i. Does the type of mission affect this anticipation?

B. Does the possibility of lost link affect your projection of unmanned aircraft in the future, yes or no?

5. Imagine a scenario where a manned aircraft and an unmanned aircraft are approaching (non-urgent case). Who would you contact first to issue a command to maneuver in order to **maintain separation**?

A. If the manned aircraft was flying under Instrument Flight Rules and the unmanned aircraft was flying under Instrument Flight Rules.

B. If the manned aircraft was flying under Instrument Flight Rules and the unmanned aircraft was flying under Visual Flight Rules with flight following.

C. If the manned aircraft was flying under Visual Flight Rules with flight following and the unmanned aircraft was flying under Instrument Flight Rules.

D. Why would you contact them first?
   After the initial response, ask these follow-up questions if not cited previously.
   i. Are you more confident in one category of aircraft (manned or unmanned) implementing your commanded maneuver within time to prevent a near mid-air collision?
   ii. Are you concerned with speed of response limitations in one category of aircraft?
   iii. Are you concerned with maneuver performance limitations in one category of aircraft?
   iv. Are you concerned with communications reliability in one category of aircraft?
   v. Are you concerned with right-of-way rules between the different categories of aircraft?
   vi. Are you concerned with the possibility of lost link in the unmanned aircraft?
   vii. Are you concerned with the lack of a see-and-avoid capability in the unmanned aircraft?
   viii. Could you rank these reasons 1-5?

E. Would the manned/unmanned distinction change the type of command you would give them?

6. Imagine a scenario where, for a reason not attributed to you, a manned aircraft and an unmanned aircraft are in conflict (Urgent case). (In this given scenario, all other variables are the same…) Who would you contact first to issue a command to maneuver in order to **avoid a collision**?

7. Do you trust a manned aircraft and unmanned aircraft equally, yes or no?

  A. If no, which category of aircraft (manned or unmanned) do you trust more?
     i. These answers can be a gradient or mixed…
  B. If no, what causes you to trust a manned/unmanned aircraft less than an unmanned/manned aircraft?
     After the initial response, ask these follow-up questions if not cited previously.
     i. Do these answers vary depending on the type of unmanned aircraft?
  B. If no, does this cause you to control the aircraft differently?

8. Do you think a manned aircraft pilot and an unmanned aircraft system operator has the same amount of situation awareness, yes or no?

  A. If no, do you change your control strategies to compensate for their perceived lower situation awareness, yes or no?
     i. If yes, what do you do differently?
  B. If no, do you think they require the same amount of situation awareness, yes or no?

9. Generally, what have your experiences been controlling unmanned aircraft: positive, negative, or neutral?

  A. What are your biggest challenges controlling unmanned aircraft?
  B. Have you had a specific issue involving an unmanned aircraft?

10. When considering integrating unmanned aircraft into the National Airspace System, what do you think are some key issues or concerns that need to be addressed?

Low-Priority Additional Questions

1. What UAS-specific training would you have liked to receive that you didn't?

2. Do you make assumptions about the level of training or level of competency of unmanned or manned aircraft operators or pilots based on the type of aircraft they fly, yes or no?

  A. If yes, could you tell me what types of aircraft have distinguishing levels of competency?
  B. If yes, how does this affect the way you control them?
  C. If yes, what do the different pilots/operators do differently?
  D. If no, do you make assumptions based on the organization they fly with? (Specific unit, military versus civilian)

3. Do you think about an unmanned aircraft system operator the same way you think about a manned aircraft pilot?

  A. If no, how do you think about them differently?
  B. If yes, do you conceptualize them being inside the unmanned aircraft or being separate from the unmanned aircraft?
  C. Does physical risk to pilots and passengers versus physical risk to unmanned aircraft operators weight into decisions?

4. What conditions would be necessary for you to control unmanned aircraft the same way you control manned aircraft?

Appendix F: VFR Separation Criteria at Field Sites

ATC Facility	Class Airspace	IFR		VFR	
		Vertical (feet)	Horizontal (miles)	Vertical (feet)	Horizontal (miles)
FAA-Terminal[a]	Class C	1,000	3	500[b]	target resolution[b]
FAA-Terminal[c]	Class D	1,000	3	sequencing/ advisories[d]	sequencing/ advisories[d]
FAA-Terminal[e]	Class E	1,000	3	advisories[f]	advisories[f]
Cannon AFB Tower	Class D	1,000	3	1,000[g]	3[g]
Cannon AFB RAPCON	Class E	1,000	3	1,000	3
Holloman AFB Tower	Class D	1,000	3	500[g]	3[g]
White Sands Missile Range RAPCON	Restricted	1,000	3	500	3
Beale AFB Tower	Class C	1,000[d]	3	1,000[g,h]	500 feet[g,i]
Edwards AFB Tower	Class D	sanitized[j]	sanitized[j]	sanitized[j]	sanitized[j]
SPORT Military Radar Unit	Restricted	N/A[k]	N/A[k]	2,000	5
Creech AFB Tower	Class D	N/A[l]	N/A[l]	500	No RSRS[m]
Nellis AFB RAPCON	Class A	1,000	3	N/A[n]	N/A[n]

[a] The FAA has not differentiated manned and unmanned aircraft with respect to separation standards in FAAO 7110.65V or any applicable COAs. This row represents the separation standards for manned aircraft in the terminal area. VFR separation standards assume Class B or Class C airspace (FAAO 7110.65V, 2014).
[b] ATC can separate manned VFR aircraft using visual separation when one manned aircraft in sight of another manned aircraft. This is prohibited with unmanned aircraft (FAAO 7110.65V, 2014).
[c] The FAA has not differentiated manned and unmanned aircraft with respect to separation standards in FAAO 7110.65V or any applicable COAs. This row represents the separation standards for manned aircraft in the tower environment. VFR separation standards assume Class D airspace (FAAO 7110.65V, 2014).
[d] ATC provides sequencing, traffic advisories, and safety alerts (but not separation services) to VFR aircraft in Class D airspace (FAAO 7110.65V, 2014).
[e] The FAA has not differentiated manned and unmanned aircraft with respect to separation standards in FAAO 7110.65V or any applicable COAs. This row represents the separation standards for manned aircraft in the terminal environment. VFR separation standards assume Class E airspace (FAAO 7110.65V, 2014).
[f] ATC provides traffic advisories and safety alerts (but not separation services) to VFR aircraft in Class E airspace (FAAO 7110.65V, 2014).
[g] ATC can separate manned and unmanned aircraft using visual separation when ATC is in sight of both aircraft (FAAO 7110.65V, 2014).
[h] Beale AFB Tower cannot allow a manned aircraft to overfly an unmanned aircraft inside Class C airspace, regardless of separation distance. This restriction is based on the unmanned aircraft's Lost Link procedure, which causes a climb above Class C airspace boundaries (BAFBI 11-250, 2013).

[i] Beale AFB Tower can offset VFR pattern traffic 500 feet laterally from RQ-4s on departure. However, this is procedurally de-conflicted with all RQ-4s making an initial western turnout with additional vertical separation during the maneuver (BAFBI 11-250, 2013).
[j] Edwards AFB Tower must sanitize all Class D airspace south of the active runway for Global Hawk operations. Only north patterns and straight-ins are authorized while the Global Hawk is in Class D airspace (EAFBI 13-100, 2014).
[k] SPORT MRU provides VFR de-confliction services only. They are not certified to provide IFR separation (EAFBI 13-100, 2014).
[l] Creech AFB Tower is a VFR airfield (CAFBI 11-250, 2015).
[m] Creech AFB Tower will provide Class D VFR services. However, unmanned aircraft are not allowed to accept Reduced Same Runway Separation (RSRS), which limits their lateral spacing on the runway, unlike many military aircraft. In addition, the Supervisor Of Flying (SOF) has the ability to limit the number of unmanned aircraft due to saturation, unlike manned aircraft (CAFBI 11-250, 2015).
[n] Nellis AFB RAPCON only controls unmanned aircraft in Class A airspace (IFR flight plans) according to NAFBI 11-250 and applicable COAs (NAFBI 11-250, 2013).

Appendix G: Subject Matter Expert Qualifications

The researcher's qualifications include the following experiential knowledge:

- Formal education
  - B.S. Aeronautical and Astronautical Engineering, Purdue University
  - M.S. Aviation Systems, University of Tennessee Space Institute
  - M.S. Flight Test Engineering, United State Air Force Test Pilot School
- Flying qualifications
  - Airline Transport Pilot, Airplane Multiengine Land, BBD-700, BE-200
  - Commercial Pilot, Airplane Single Engine Land, Glider
  - Certificated Flight Instructor, Airplane Single and Multiengine, Instrument Airplane, Glider
  - United States Air Force Command Pilot
  - United States Air Force Test Pilot School Graduate
- Flying experience
  - 2,675 hours flight time
- Air traffic control experience
  - Supervisor of flying (aircrew position in military control tower) for over 5 years
  - Air boss (aircrew position in military airspace control facility) for over 1 year